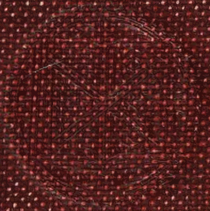


Digitized by the Internet Archive
in 2022 with funding from
Kahle/Austin Foundation

https://archive.org/details/geologyofpetrole0000erne

The Geology of Petroleum and Natural Gas

BY

ERNEST RAYMOND LILLEY, SC.D.
Associate Professor of Geology at New York University
Author of "The Oil Industry."

NEW YORK
D. VAN NOSTRAND COMPANY, INC.
EIGHT WARREN STREET
1928

Copyright, 1928, by
D. VAN NOSTRAND COMPANY, Inc.

All rights reserved, including that of translation into the Scandinavian and other foreign languages.

UNIVERSITY OF ARIZONA
553.28
E72
LIBRARY

Printed in the United States of America

LANCASTER PRESS, INC.
LANCASTER, PA.

PREFACE.

The development of the petroleum and natural gas industries dates from the completion of a producing oil well of a depth of 69 feet near Titusville in Pennsylvania in 1859. Oil had been secured from shallow pits and hand dug wells in many areas before this, but the commercial value of such sources had been insignificant. The Titusville well did not even have the distinction of being the first drilled well to produce oil. Others sunk primarily in search for salt enjoyed that honor. It was, however, the first well that was drilled with the hope of getting oil, the first successful wildcat well.

Thus, while our knowledge of the character and origin of many mineral deposits is the product of the accumulation of data over a number of centuries, the science of petroleum geology is based upon information which has been obtained in a period of less than seventy years. In this short period, however, the oil industry has grown from nothing into one of the outstanding industries of the world. During the year of 1927, the production of the United States was equal to approximately nine hundred million barrels of oil. The total for the whole world for the same period was more than a billion and a quarter barrels. In sections where it could be marketed, the rise in the production of natural gas has been almost as sensational.

The ideas of Colonel Drake, the pioneer under whose direction this unprecedented test was sunk, will probably never be known. That he had little or no knowledge of geology is generally admitted but luckily for the development of the industry his chance location was made at a point in which oil was available in commercial quantities at an extremely shallow depth. His crude drilling tools would hardly have been adequate for a much greater depth even if his faith had been strong enough to desire it.

The sole reason for the venture seems to have been the feeling on the part of Drake that the seepages along Oil Creek were fed by underground bodies of oil. His success there quickly led others all over the world to sink test wells at points near seepage indications. Many of the discovery wells of the world's most prominent producing pools and districts were located solely upon this basis. The tremendous volume of the oil produced in the vicinity of seepages in the Baku district of

69149

Russia tended to discourage drilling of wells in sections distant from them. In the Appalachian area of the United States seepages were few in number and individual wells were small in size. With a steadily increasing demand for their product, operators ventured farther and farther away from seepages and found that large producing areas might occur many miles from such indications. The controlling factor appeared to be the presence or absence of certain sands. Prospectors, therefore, deliberately limited their activities to those sections in which these sands were believed to occur.

The association of oil and gas with water was recognized early in the history of the development of Pennsylvania. It was soon realized that there was a definite relationship between the distribution of these substances in a given sand and the depth at which the sand was reached. Those wells which penetrated the sand horizon at shallow depths were found to be productive of oil and gas far more frequently than those which had to be drilled to greater depths. Naturally operators restricted their efforts to the former as much as their limited knowledge would permit.

The reduction of the loosely formulated rules of the game of wildcatting into the scientific principles of the gravitational or anticlinal theory was largely due to the efforts of Dr. I. C. White, whose first statement of it was published in 1885. The theory is simple but its application is frequently complex. The ideal point of accumulation according to the theory is the crest of an anticline. However, the fault, the unconformity, the lens, and the salt dome may serve just as well. Variations in porosity of rocks cause modifications because of the introduction of the force of capillarity. Similarly the hydraulic action of artesian waters may cause further modification of the positions most favorable for accumulation.

Knowledge of the importance of different structural conditions and of the effects of such modifying agencies can only be acquired through scientific examination of an abundance of data. The zeal for the conduct of such investigations depends largely upon the returns secured from them. In the United States, the rapidity of the expansion of markets for oil and gas—particularly since the advent of the automobile, the inability of individual pools and districts to supply the increasing demands, and the high cost of drilling to deep horizons, all served to encourage research on a larger scale than in any other section of the world. As the presence of oil in most of the larger areas now producing was first demonstrated by the presence of seepages or by the drill of the wildcatter whose location was determined entirely by chance, the work of the geologist was largely restricted to studies of the relationships between oil and gas accumulation and structural conditions.

Despite temporary periods of overproduction the American oil producer realizes that he is never far ahead of the consumer. The demands of the market have only been satisfied by the development of new areas in which surface indications of oil are meager and by the drilling of wells to increasing depths and into formations below major unconformities. Whereas discussions of the origin of petroleum, natural gas, and related bitumens, of the conditions controlling their formation, and of the factors influencing their subsequent alteration were primarily of academic interest a few years ago, it is now realized that knowledge of these subjects is of material assistance in the search for new oil areas. The petroleum geologist recognizes that the proper application of such knowledge requires that he devote himself to the study of historical geology, including both paleogeography and paleontology, in the same way that he has devoted himself to the study of structural geology in attempting to locate new areas of local accumulation.

Much remains to be done in practically every division of the geology of oil and gas. Additions to our knowledge are being made every day. Yet, it is necessary from time to time that we stop and summarize the data that have become available. The mass of descriptive detail now available has reached tremendous proportions and is being increased with every issue of our trade and technical journals. It is now almost impossible for even the individual who is actively practicing the profession of petroleum geology to keep up with its literature. This book has been written to supply to such individuals and to others, whose work brings them into contact with geologic problems in the field of oil and gas, a single volume in which they may find brief statements of principles of the science and examples illustrative of the application of those principles. It is further hoped that the student who is preparing to enter this field of work will find in it an adequate statement of the principles that he is studying.

No claim of completeness is put forward by the author. It is no longer possible for one individual to consult more than a small portion of the literature which has become available. The necessity of restricting the length of the volume to a size usable for text and general reference purposes makes necessary the omission of many illustrations and examples equal in value to those which have been included. Similarly it has been necessary to pass over many important contributions to the development of our basic principles with single sentences. Many could not be discussed at all. The author keenly regrets this. He has tried to give acknowledgments to those whose work has been of especial importance. In the selection of examples and references he has felt obliged to give preference to those which the reader who desired further information would be most likely to find in public, technical society, and university libraries in the United States.

The author has endeavored throughout the volume to give full acknowledgment to both the authorities quoted and to the organizations that published the original papers. He desires to make additional acknowledgments here to several of the latter because of the number of illustrations and tables used, namely, American Association of Petroleum Geologists, American Institute of Mining and Metallurgical Engineers, Geological Society of America, Economic Geology, Journal of Geology, Oil and Gas Journal, United States Geological Survey, United States Bureau of Mines, and California Division of Mines and Mining (California Oil Fields). The author wishes also to express his appreciation to Mr. F. G. Clapp for the use of two unpublished maps. Grateful acknowledgment is also due to my wife, Antoinette Lilley, for her careful and able assistance in both the preparation of the manuscript and the reading of the proofs.

Ernest R. Lilley.

New York, N. Y.,
March, 1928.

CONTENTS.

CHAPTER PAGE

I—INTRODUCTION 1

The Nature of Petroleum—Substances Allied with Petroleum—The Science of Petroleum Geology—Utilization of Geology—Terminology.

II—SOME PROPERTIES OF PETROLEUM 15

Color—Odor—Density—Viscosity—Coefficient of Expansion—Volatility—Solidification—Surface Tension and Capillary Action—Optical Activity—Other Physical Properties—Chemical Composition—Hydrocarbons—Paraffin Series—Isomeric Compounds—Olefine Series—Other Alipathic Compounds—Naphthene Series—Benzene Series—Other Ring Compounds—Sulphur Compounds—Oxygen Compounds—Nitrogen Compounds—Other Ingredients in Petroleum—The Base of Oils.

III—MINERAL BITUMENS RELATED TO PETROLEUM 36

Classification of Bitumens—Natural Gas—Natural Asphalt—Soft Asphalts—Asphaltites—Mineral Waxes—Pyrobitumens—Bituminous Rocks—Kerogen or Oil Shale—Nature of Kerogen—Coals—Cannel Coals.

IV—THE ORIGIN OF PETROLEUM AND RELATED SUBSTANCES 53

Inorganic Theories—The Carbide Theory—Application of Inorganic Theories—Berthelot's Theory—Mendeléef's Theory—Direct Evidence of Inorganc Origin—Indirect Evidence—Insufficiency of Inorganic Theories—Organic Theories—Source Materials of Petroleum—Animal Theories—Plant or Vegetable Sources—Comparative Importance of Different Materials—Manner of Deposition and Accumulation—Anerobic Bacterial Action—The Nature and Alteration of Kerogen—Nature of Oils—Hydrogenation of Oils—Removal of Heavy Compounds—Internal Alteration of Hydrocarbons—Carbomorphism of Coals—Destruction of Hydrocarbons—Effects of Sulphur on Oils—Conversion of Oils to Solids—Pyrobitumens—Summary.

V—FUNDAMENTAL GEOLOGIC CONDITIONS LIMITING THE OCCURRENCE OF PETROLEUM 89

Ingenous Rocks—Sedimentary Rocks—Glacial Deposits—Desert Deposits—Cut-off Basin Deposits—Sediments of Humid Areas—Coastal Swamps—Deep Sea Deposits—Near Shore Sediments—The Deposition of Organic Debris—The Functions of Metamorphic

CHAPTER PAGE

Agencies—Metamorphosed Rocks as Sources of Oil—Comparative Alteration of Coal and Petroleum—Summary.

VI—GEOLOGIC HISTORY AND THE OCCURRENCE OF OIL 115

Pre-Cambrian Rocks—The Cambrian Period—Ordovician History—Ordovician Oil—Silurian History—Silurian Oil—The Cincinnati Uplift—Devonian Conditions—Devonian as a Source of Oil—Mississippian Conditions—Mississippian Oil—Pennsylvanian History—Pennsylvanian Oil—Permian Conditions—Permian Oil—The Paleozoic as an Oil-yielding Era—Mesozoic Conditions—Triassic Oil—Jurassic Conditions—Oil in the Jurassic—Lower Cretaceous History—Lower Cretaceous Oil—Upper Cretaceous—Cretaceous in Other Continents—Upper Cretaceous Oils—The Mesozoic as an Oil-yielding Era—Cenozoic Conditions—North American Tertiary—The Tertiary in Other Continents—Tertiary Oil—Quaternary Horizons—Tertiary as a Container of Oil.

VII—PETROLEUM RESERVOIR ROCKS 159

Containers and Retainers—Capillary Openings—Origin of Openings—Shape of Particles—Assortment and Arrangement—Simultaneous Cementing—Later Cementing—Compacting—Solution Openings—Recrystallization—Crustal Movements—Weathering of Rocks—Nature of Rocks—Sands and Sandstones—Determination of Porosity—Nature of Sands—Sandstones as Retainers—Conglomerates—Limestones—Limestones as Retainers—Clays and Shales—Hybrid Rocks—Minor Sedimentary Rocks—Metamorphic and Igneous Rocks—Containers versus Retainers.

VIII—THE CONCENTRATION OF OIL AND GAS 181

Oilfield Waters—The Gravitational Theory—History of the Theory—Expulsion of Oil from Non-porous Rocks—Manner of Accumulation—Objections to the Theory—The Hydraulic Theory—Capillarity as a Means of Concentration—The Function of Gas—Effects of Temperature—Effects of Diastrophic Movement—Pressure in Oil and Gas Horizons—Summary.

IX—THE REPRESENTATION OF STRUCTURAL CONDITIONS 208

Photographs—Surface Geology Maps—Strike and Dip Symbol Maps—Contour Maps—Errors in Mapping—The Columnar Section—Well Logs—Cross-sections—Subsurface Maps—Convergence Maps—Sand Maps—Stereograms—Models—Summary.

X—THE NATURE OF OIL FIELD STRUCTURES 232

XI—THE DEVELOPMENT OF FOLDED AND FAULTED STRUCTURES 235

Differential Compacting—Nature of Crustal Deformation—Competency of Rocks—Horizontal Trust Structures—Direct Uplifts—Causes of Faulting—Extent of Faults—Summary.

XII—CHARACTERISTICS OF FOLDED STRUCTURES 251

Simple Symmetrical Anticlines—Sante Fe Springs, California—Upright Asymmetrical Anticlines—Long Beach, California—Do-

CHAPTER PAGE

minguez, California—Inclined Asymmetrical Anticlines—Yenangyat-Singu Anticline, Burma—Wheeler Ridge, California—Anticlines with Curved Axes—Grass Creek, Wyoming—Domes or Quaquaversal Anticlines—Petrolia, Texas—Bald Hill Dome, Oklahoma—Hogback Dome, New Mexico—Lost Soldier Dome, Wyoming—Cotton Valley, Louisiana—Terraces and Plunging Anticlines—Eastern Osage, Oklahoma—Berea Grit Pools, Ohio—Osage Pool, Wyoming—Broad Anticlinal Folds—Monroe Gas Pool, Louisiana—Saddles—Cement Anticline, Oklahoma—Torchlight and Lamb, Wyoming—Pershing Pool, Oklahoma—Synclines—Midway Valley Syncline, California—Asphalt Sealed Traps—Sunset Area, California—Overturned Folds—McKittrick Overturned Fold, California—Summary.

XIII—STRUCTURES DOMINATED BY FAULTING 309

Luling-Mexia and Balcones Fault Zones—The Mexia Fault Zone—The Luling Fault—Irvine-Paint Creek Fault—Whittier Fault—The Whittier Pool—Brea Canyon-Olinda—Santa Clara Fault—South Mountain—Overthrust Faults, McKittrick, California—Summary.

XIV—ACCUMULATIONS CONTROLLED BY POROSITY VARIATIONS 339

Lensing Sands—Clinton Sand, Ohio—Horizons of Varying Porosity—Glenn Pool, Oklahoma—Burbank Pool, Oklahoma—Minor Producing Areas—Pools at Unconformable Contacts—Sunset Extension, California—Maikop, Russia—Channel Deposits—''Shoe String Sands,'' Eastern Kansas—Large Elongated Sand Bodies—Hogshooter String—Summary—Production from Fissures.

XV—IGNEOUS ROCKS AS OIL CONTAINERS 368

Furbero—Thrall and Lockhart—Akita and Related Districts, Japan—Contact Zone Production—Summary.

XVI—SALT CORE STRUCTURES 376

The Salt Masses of Germany—Roumanian Salt Domes—Oil Production of European Salt Structures—Isthmuthian Domes of Mexico—Salt Domes of the Interior Gulf Coast Plain—Gulf Coast Domes—Oil in the Gulf Coast Domes—Theoretical Problems Connected with Salt Domes—Source of the Salt—Mechanics of Uplift—Hager's Igneous Intrusion Theory—Crystal Growth Theory—Plastic Flow Theory—Period of Folding and Uplift in Gulf Area—Salt Dome Cap Rocks—Conclusions.

XVII—ACCUMULATIONS CONTROLLED BY SEVERAL FACTORS 408

Simultaneous Sedimentation and Folding—Variations in Competency—Vertical Range of Faults—Burial of Structures—Revival of Dynamic Activity—Accumulations at Unconformities—Order of Discussion—Ranger Area, North Texas—La Salle Anticline, Illinois and Indiana—Kevin-Sunburst Area, Montana—Binagadi, Russia—Inglewood, California—Hubbard Pool, Oklahoma—Salt Creek, Wyoming—Cat Creek, Montana—Big Lake Pool, Texas—Healdton, Oklahoma—Robberson Pool, Oklahoma—Panhandle Struc-

CHAPTER PAGE
ture, West Texas—Gemsah and Hurghada, Egypt—Maidan-I-Naftun, Persia—The Granite Ridge of Kansas—Eldorado and Augusta, Kansas—Cushing, Oklahoma—Seminole District, Oklahoma—Tonkawa, Oklahoma—Thomas Pool, Oklahoma—Tamasopo Ridge, Mexico—Summary.

XVIII—Exploration of New Areas 479
Oil Seepages—Gas Seepages—Mud Volcanoes—Solid Petroleum Residues—Local Structural Conditions—Diamond Drilling for Structure—Geophysical Prospecting—Subsurface Tools—Limitation of Geologic Activity—Non-producing Structures.

Author Index 503

Subject Index 508

CHAPTER I.

INTRODUCTION.

The Nature of Petroleum.—The dictionary describes petroleum as an inflammable oily liquid which exudes or is pumped from the earth. The more complete editions add that it is used chiefly in the production of gasoline, kerosene, lubricating oils, fuel oils, asphalts, and waxes.

The wide variety of the properties of these and other less prominent products proves the extremely complex nature of the substance. Most petroleums are composed primarily of the true hydrocarbons, that is, compounds containing only hydrogen and carbon. The number of such compounds is large. The majority of those that have been identified in petroleum are liquids, but gaseous and solid compounds have been found dissolved in crude oils. The hydrocarbons are divided into groups or families, which are characterized by different chemical and physical properties. Those most desired by the refiner and by the consumer of petroleum products are those that are the most stable, chemically.

Of these the paraffin and naphthene families stand out. The diolefines, triolefines, and similar chemically unstable, unsaturated compounds are most undesirable. Other series, such as the benzenes and the olefines, are desirable in some products and undesirable in others. Compounds of these two groups are usually present in only small amounts in most petroleums. The paraffin compounds predominate in the "paraffin base" oils of the Appalachian area of the United States and in the oils from the older horizons of Kansas and Oklahoma. Appreciable amounts are present in all oils of low density. The naphthene compounds are much heavier than those of the paraffin group, which they resemble most closely. They constitute a large percentage of the crude oils obtained in California, South Texas, and similar areas.

Petroleums that contain large amounts of paraffin compounds usually contain relatively small amounts of the unsaturated, unstable types. Many of the oils in which naphthene compounds are prominent are also containers of large percentages of the unstable, unsaturated types. These tend to form asphalts on exposure to heat or chemical agents. Thus such oils are known commonly as "asphaltic base" oils, though the amount of dissolved asphalt may be small as the crude oil is taken from the ground.

Some crude oils contain substantial amounts of sulphur; others, appreciable percentages of nitrogen or oxygen. In general, the proportion of these elements and of the compounds containing them is largest in the heavier types of oil. Thus such elements may be considered as more characteristic of asphaltic base oils than of the paraffin type. They are, however, not entirely lacking in the lighter oils.

Substances Allied with Petroleum.—The liquid petroleum is chemically and geographically closely related to the solid asphalts, asphaltites, pyrobitumens, natural waxes, and to natural gas. Tar or asphalt saturated sands mark the edges of productive oil areas in several pools in the Valley field of California. Natural gas is produced from the same wells that yield oil and is considered by many to be the most important force causing the movement of oil through the small pore spaces of the rocks containing it.

In the great majority of the world's producing areas, oil is found in porous rocks that appear to be saturated with water. In the fields of the United States that yield oil from Paleozoic horizons, the water appears to be closely related chemically to ocean water. The percentage of salts dissolved is usually higher than that of ocean water, but the relative proportions of the different elements and compounds present show much similarity. In other areas, such as the Rocky Mountain Province, the close association of oil and water is maintained, but the salts present are entirely different from those of ocean waters. Some analyses show the presence of salts that are typical of soil and artesian waters. In California, mixed types, having characteristics between artesian and ocean waters, have been found associated with oil. Variations in characteristics of both oil and water appear to have resulted locally from the interaction of the less stable compounds in the petroleum and the salts dissolved in the waters. In many instances the changes in the oil have been sufficient to convert it to a solid asphaltic substance.

The mobility of petroleum and natural gas has made it possible for these substances to circulate through porous rocks and even to escape to the surface. Despite this freedom of movement, commercial concentrations of oil are almost always found in close proximity to beds of carbonaceous or kerogenetic shales, the source materials from which they are considered to have been derived. The carbonaceous matter of such beds cannot be considered as chemically identical with that of petroleum, but the close relationship is indicated by the similarity of the oil which may be secured by destructive distillation of the kerogen of the shales.

The carbonaceous or kerogenetic matter of such shales differs but slightly from that in cannel coals. The latter in turn are closely related to the normal types of coals. Though differing in many respects, normal coals and petroleum have so many chemical properties in common and are so closely related in geographical and geological distribution that there is ample evidence to warrant the belief that they are genetically related.

The Science of Petroleum Geology.—While petroleum, natural gas, and the asphaltic and paraffinaceous solids most closely related to them have been known for many centuries, the scientific study of their occurrence and origin is comparatively modern. It may be said to have followed the completion of the first drilled well in Pennsylvania in 1859. The growth of knowledge has followed much the same course as the development of the industry. The yearly production of oil did not reach the hundred-million-barrel mark until 1895. The half-billion mark was attained in 1917; and the billion mark, only six years later. The two fundamental principles upon which the science of petroleum geology is based—the organic theory of origin and the gravitational theory of accumulation—were little more than unsubstantiated hypotheses at the close of the nineteenth century. Their general concepts have been substantiated many times by the developments of the present century. At the same time new producing areas and deeper horizons have made it necessary to modify previously conceived ideas, and have made it possible to fill in points about which information was almost entirely lacking.

Those theories which explain the origin and formation of petroleum and natural gas should form the basis of a working hypothesis for the search for oil in new areas. Such localities are frequently indicated by the presence of active oil and gas seepages, mud volcanoes, and asphalt deposits. They are most marked in Tertiary and Cretaceous areas. However, surface indications are not always pronounced. Their absence in any area cannot be considered as a definite indication of the absence of petroleum. Such indications have been of very minor importance in the development of the producing areas of the Paleozoic horizons of the Mid-Continent and the Eastern Provinces of the United States.

Table 1.—World Production of Petroleum in Barrels of 42 Gallons.*

Country	1927 ‡	1926	1925	1857–1924	Year of Initial Production
United States	903,800,000	770,874,000	763,743,000	7,905,929,000	1859
Russia	72,400,000	64,311,000	52,448,000	2,053,183,000	1863
Venezuela	64,400,000	37,226,000	19,687,000	18,812,000	1917
Mexico	64,200,000	90,421,000	115,515,000	1,194,991,000	1901
Persia	36,800,000	35,842,000	35,038,000	147,522,000	1913
Rumania	26,100,000	23,314,000	16,650,000	207,842,000	Prior to 1857
Netherlands East Indies	21,400,000	21,242,000	21,422,000	294,030,000	1893
Colombia	14,600,000	6,444,000	1,007,000	1,192,000	1922
Peru	9,800,000	10,762,000	9,252,000	52,321,000	1896
Argentina	8,700,000	7,952,000	6,336,000	20,421,000	1908
British India	8,200,000	8,728,000	8,274,000	157,546,000	1889
Poland	5,800,000	5,844,000	5,960,000	190,633,000	1874
Trinidad	5,200,000	5,278,000	4,387,000	23,264,000	1909
Sarawak	5,000,000	4,942,000	4,257,000	16,505,000	1913
Japan and Formosa	1,700,000	1,900,000	1,694,000	49,496,000	1913
Egypt	1,270,000	1,188,000	1,226,000	11,758,000	1875
Germany	700,000	653,000	541,000	16,739,000	1911
France	525,000	478,000	459,000	2,858,000	1880
Canada	500,000	364,000	332,000	25,561,000	1862
Ecuador	450,000	214,000	160,000	Included in total	1921
Sakhalin	200,000	181,000	87,000	—	1925
Czechoslovakia	140,000	150,000	158,000	481,000	1919
Italy	60,000	48,000	70,000	1,186,000	Prior to 1857
Totals †	1,252,145,000	1,098,389,000	1,068,741,000	12,392,541,000	

* After U. S. Bureau of Mines, U. S. Geological Survey, and U. S. Bureau of Foreign and Domestic Commerce.

† Includes small amounts from other countries.

‡ Preliminary estimate.

Areas being developed today outside of North America are almost exclusively in sections where the strata are of Tertiary age. The future will undoubtedly see the development of areas of older rocks in which surface indications are either slight or entirely lacking. Much oil is to be expected from deeply buried horizons whose outcrops are unknown. In such sections and horizons the mere existence of petroleum is unproved. The recommendation of the geologist must be based upon indirect evidence: the characteristics of the rocks as shown at their outcrops or by drill samples, and the presence of oil in rocks of similar type and age in other areas. The greater part of the initial work of exploration must be devoted to study of purely non-economic phases of the geology of the region and comparisons of the data obtained, with conditions existing in known productive areas.

Neither surface indications nor favorable indirect data are a guarantee that commercial quantities of oil exist. In some areas the previous existence of oil is apparent, but the bulk of it has escaped or been destroyed. Even when it still remains, the amount is never sufficient to make commercially productive areas continuous. The limited extent of commercially valuable accumulations is marked in every fully developed pool in the world by dry holes and abandoned wells. Some dry holes are actually dry, but the majority contain water in the horizons from which oil is obtained in adjacent areas.

In the great majority of cases the water lies in the lower or basinal portions of folded or tilted, porous sedimentary beds lying between non-porous ones. The upper or arched portions of the same beds contain the oil and gas. From this it is apparent that the position of folds and faults is an important factor in determining the position of oil and gas as against water. The geologist, who feels satisfied as to the probable presence of petroleum in any given area, is then called upon to begin the study of its structural conditions to determine the positions most suited for accumulation.

The zonal arrangement of gas, oil, and water, which characterizes every large producing area in the world, indicates a certain amount of freedom of movement of those substances within the crust of the earth. Such movement can only occur in those portions of the crust in which the formations are sufficiently porous to permit gravitational and capillary differences to result in movement. Thus, in many areas, accumulation is due as much to variations in the porosity of the strata into which the oil has migrated after its formation as to their struc-

TABLE 2.—PETROLEUM PRODUCTION OF THE UNITED STATES IN BARRELS OF 42 U. S. GALLONS.[*]

State	1927	1926	1925	1859–1924	Year of First Production
Arkansas	40,179,000	58,332,000	77,398,000	105,823,000	1921
California	230,752,000	224,673,000	232,492,000	2,057,660,000	1876
Colorado	2,787,000	2,768,000	1,226,000	12,287,000	1887
Illinois	7,024,000	7,760,000	7,863,000	357,173,000	1889
Indiana	852,000	808,000	829,000	112,246,000	1889
Kansas	40,740,000	41,498,000	38,357,000	345,811,000	1889
Kentucky	6,733,000	6,274,000	6,759,000	69,670,200	1883
Louisiana	21,061,000	23,201,000	20,272,000	312,194,000	1902
Michigan	435,000	94,000	4,000	[‡]	1907
Montana	5,048,000	7,727,000	4,091,000	10,199,000	1916
New Mexico	1,203,000	1,666,000	1,060,000	98,000	1913
New York	2,239,000	1,956,000	1,695,000	59,882,000 [§]	[§]
Ohio	7,529,000	7,272,000	7,212,000	506,515,000	1876
Oklahoma	277,274,000	179,195,000	176,768,000	1,643,109,000	1891
Pennsylvania	9,596,000	8,961,000	8,097,000	780,269,000	1859
Tennessee	60,000	43,000	24,000	89,800 [‖]	1883
Texas	213,768,000	166,916,000	144,648,000	994,179,000	1889
West Virginia	6,009,000	5,946,000	5,763,000	338,172,000	1876
Wyoming	21,146,000	25,776,000	29,173,000	200,354,000	1894
Total	894,435,000 [†]	770,874,000	763,743,000	7,905,929,000 [¶]	1859

[*] After U. S. Bureau of Mines and U. S. Geological Survey.

[†] Preliminary figures prepared by U. S. Bureau of Mines. Final figures include petroleum consumed on leases and produced but not transported from producing properties. This adds approximately one percent to the total.

[‡] Included in total.

[§] Early development and production records of New York and Pennsylvania not separated.

[‖] Part of Tennessee total included in Kentucky.

[¶] Includes small amounts not separated by states.

tural outline. Such differences are due mainly to conditions existing at the time of the deposition of the sediments and to cementation and solutional activity after that period. The scientific development of areas controlled by such factors is still in its infancy though much information about them is now being accumulated.

Utilization of Geology.—Prior to the present century, the development of oil producing areas was largely carried out without the assistance of the geologist. The two great producing areas were the Appalachian field of the United States and the Baku district of Russia. The presence of oil in the latter was known in Biblical times because of the abundance of oil and gas seepages. The seemingly inexhaustible supply of oil to be had merely by drilling did not encourage careful study of the manner of its occurrence and of the conditions which had caused its formation and accumulation.

Seepages must also be considered as being responsible for the drilling of the first wells in Pennsylvania. The seepages were small, and areas of production were soon found to extend to sections in which no seepages were known. The small size of the wells and the rapidly expanding demand for the product encouraged prospecting and developed a strong interest in the study of the factors which had been instrumental in the formation and accumulation of the oil. The complexity of the structural and porosity factors that controlled accumulation here retarded the development of satisfactory theories for many years. Yet the development of the gravitational or anticlinal theory is due largely to the observations of men who worked in this area.

Early locations in Pennsylvania were made largely upon the "hunch" of the operator. Such methods were soon succeeded by semi-scientific locations based upon previous experience. Well sites were placed adjacent to topographic features similar to those noted in other areas. As many of these had similar underlying geologic causes, the results were frequently excellent. "Following the trend" —a method of limiting test holes to areas between productive pools, or to sections that would lie in the extensions of lines connecting them—proved to be very successful, although the scientific principles causing the success were not known.

Similarly the operator came to realize from experience that certain horizons held little promise of containing oil. Comparisons between their physical properties and those of the productive ones suggested many conclusions about the conditions surrounding the presence of oil. While the statement of the carbon ratio theory of the conversion of oil into gas and the destruction of the gas by metamorphic agencies did not come until after the area had been largely developed, the operator early recognized that, despite the continuity of the horizons which are productive in western Pennsylvania into the central part of the state, the chances of finding oil in that area were very slight.

The abundance of sections in which seepages, or the drill of the "hunch" operator have indicated the general existence of petroleum, has retarded the study of the underlying conditions which control the existence of such areas. On the other hand, the prevalence of dry holes has encouraged the scientific study of the factors that control the localization of its accumulation. The gravitational theory was outlined in a general way shortly after the discovery of commercial quantities of oil in Pennsylvania. It was discredited by many but was revived by I. C. White, whose efforts were largely responsible for its general acceptance. The best examples of gravitational separation of oil, gas, and water were supplied by strong anticlinal folds. The theory became more generally known as the anticlinal theory of accumulation. The main work of the petroleum geologist until recently was that of locating areas in which anticlinal folds showed in the outcropping strata. The geologist was to a large extent merely a specialized type of surveyor.

It may be expected that the petroleum geologist of the future will need training of a much higher order than that possessed by many of his predecessors. The location of accumulations in the more complex and less clearly understood structural forms and in areas of porosity changes is undoubtedly controlled by the same principles which are effective in the simple anticline. However, the interpretation of the meager data supplied to him will require the geologist in drawing his conclusions to utilize to the maximum the experiences of others in other sections. The growing proportion of oil being obtained in the United States from complex structures and areas distant from seepages is indicative of a condition which may be expected in other portions of the world in a short time.

Terminology.—The terms used throughout the text are for the most part in common usage in textbooks of geology. Several terms have been used with a restrictive sense in descriptions of producing and potential areas in order to avoid misunderstandings that might arise if they were used in the indefinite manner which characterizes their use in trade journals and even in scientific papers. They are the terms pool, district, field, and province. The term "pool" will be used to indicate a single continuous producing area. In most cases this means the productive area of one particular fold. Thus we have the Long Beach pool in California and the Hogback pool in New Mexico. It may be a section dominated by faulting as in the case of the Luling pool in Texas. It may be an area above or adjacent to a salt dome or core, as at Spindletop or Damon Mound in southern Texas. In some instances it is an area controlled by several closely allied folds as in Osage County, Oklahoma. In the Glenn pool of Oklahoma it is an area determined by changes in porosity of the container horizons.

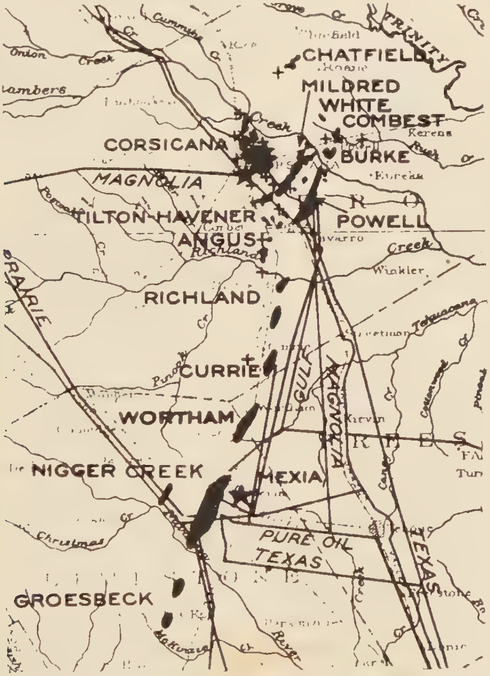


FIG. 1.—Productive areas of the Mexia District, East Central Texas, after U. S. Geological Survey, 1927.

There are very few areas in which production is limited to a single pool. Generally tests around the discovery pool lead to the finding of other pools in adjacent areas. Sometimes the areas between them are barren of oil; in others the intervening area is dotted with abandoned holes which, while productive of oil, did not yield

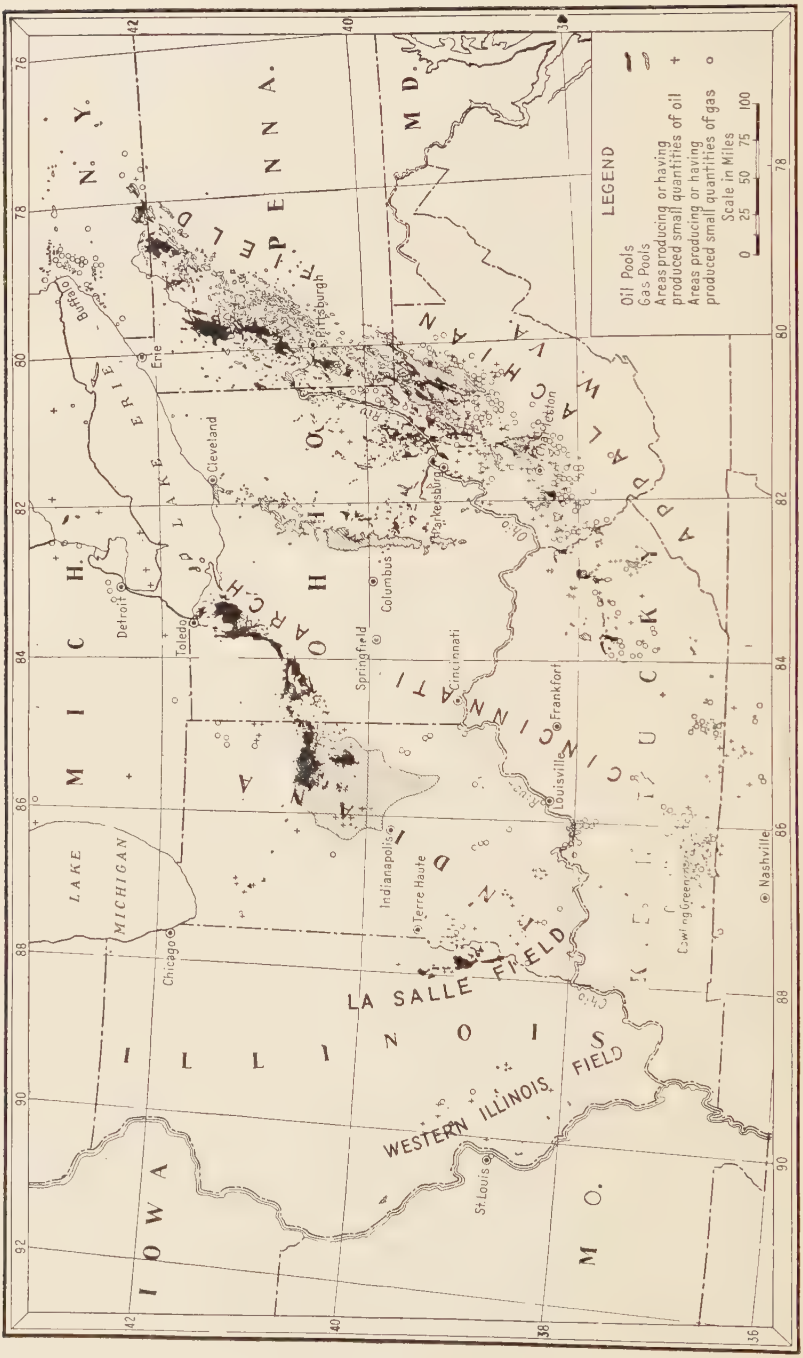


FIG. 2.—Productive Areas of the Eastern Province, After Lilley, E. R.: The Oil Industry, p. 207.

commercial quantities of it. Such pools are related to each other both from a geographical and a geological standpoint. They produce the same type of oil in most cases; they are developed under much the same conditions; and they face the same problems in obtaining supplies and marketing their products. They constitute a unit area in many respects, but the presence of non-producing sections between the productive ones distinguishes them from the pool.

They are referred to throughout the text as "districts." A typical district is found in central Texas, where the Mexia, Powell, Wortham, and several minor pools constitute the Mexia district. Similarly the sensational Seminole district of Oklahoma obtained its production in the summer of 1927 from distinct pools known as Seminole City, Seabright, Earlsboro, Bowlegs, and Little River.

The term "field" has been used in a more general sense than any of the others. Restriction of its meaning is therefore more difficult. In many writings the term is used in the same sense as the term pool. In others it refers to a section similar to that which we have called a district. Even more extensive areas may be included. In the text the author will restrict the use of the term to sections containing groups of related districts or more or less isolated pools which are related by underlying geological conditions. Where the productive beds are restricted to synclinal areas of regional size, that is considered as the limiting unit. Thus the term is used in reference to the San Joaquin Valley of California, the Big Horn Basin of Wyoming, the Maracaibo Basin of Venezuela, and the Burma syncline of India.

In a similar way the term is used in reference to groups of producing areas located upon anticlines of regional importance, such as the Bend Arch of northern Texas, the Sweetgrass uplift of northern Montana, and the Cincinnati Arch of Ohio and adjacent states. Where the synclinal basins in which the oil containing horizons occur are of extremely large area, as in the Paleozoic synclines of eastern and central portions of the United States, the term is used in reference to the area included in one flank. Thus the Appalachian field includes all of the productive areas lying on the east flank of the Appalachian geosyncline. The North Mid-Continent field similarly includes those areas on the northeast flank of the Mid-Continent geosyncline and adjacent to the old land area of Ozarkia.

The marked differences between the conditions under which oil is produced on the southward sloping coastal plain of Texas, Louisi-

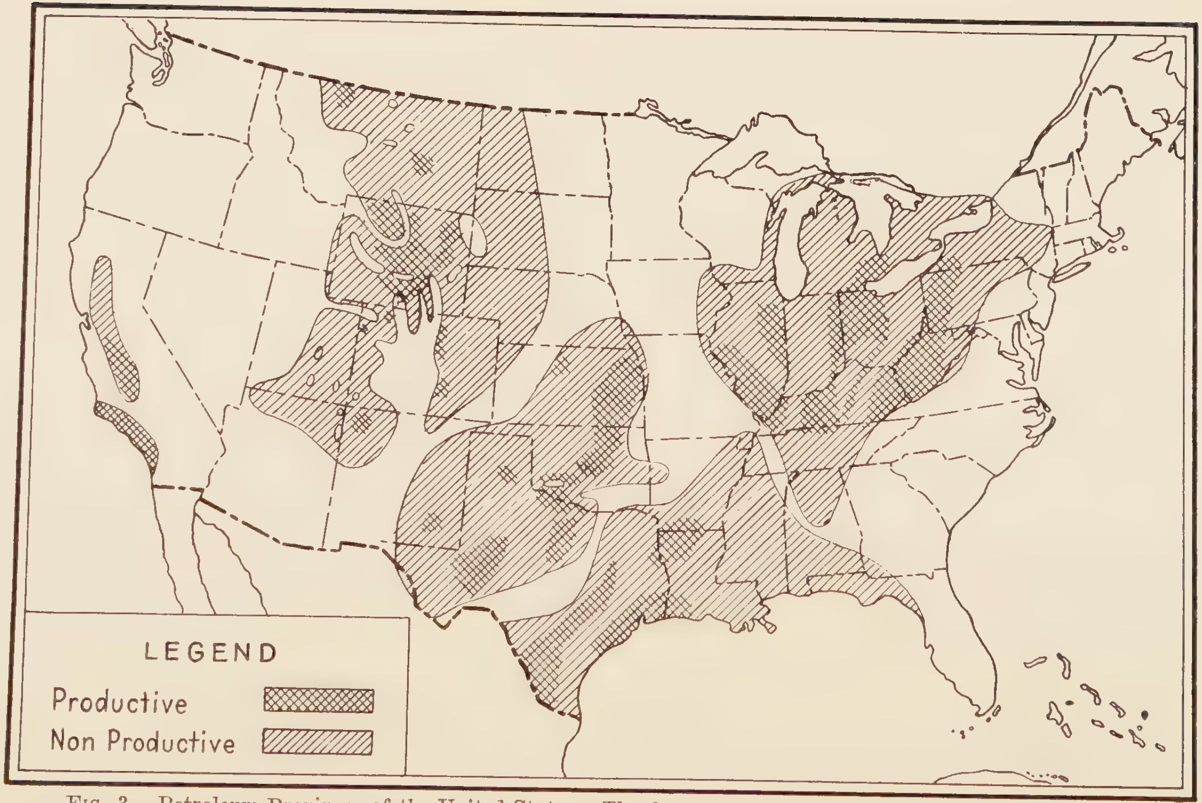


FIG. 3.—Petroleum Provinces of the United States. The five shaded areas are, from left to right, the Pacific, Rocky Mountain, Mid-Continent, Gulf, and Eastern Provinces.

ana, and Arkansas, warrant division of the area into an interior or Stratum field and a coastal or Salt Dome field despite the absence of any marked change in the regional structure.

The close relationship in origin between the oil yielding areas of California, despite the presence of non-petroliferous rocks between them, can hardly be doubted. Similarly, depositional conditions must have been much the same throughout the Paleozoic of the eastern portion of the United States. In referring to large areas of such character, the author uses the term ''province.''

A SELECTED BIBLIOGRAPHY ON THE GEOLOGY AND DISTRIBUTION OF PETROLEUM AND NATURAL GAS.

BOOKS.

1. Bacon, R. F., and Hamor, W. A., The American Petroleum Industry.
2. Cunningham-Craig, E. H., Oil Finding.
3. Day, David T., Handbook of Petroleum.
4. Emmons, W. H., Geology of Petroleum.
5. Garfias, V. R., Petroleum Resources of the World.
6. Hager, Dorsey, Practical Oil Geology.
7. Johnson, R., and Huntley, L. G., Principles of Oil and Gas Production.
8. Lilley, E. R., The Oil Industry.
9. Panyity, L. S., Prospecting for Oil and Gas.
10. Redwood, Boverton, Treatise on Petroleum.
11. Stigand, I. A., Outlines of the Occurrence and Geology of Petroleum.
12. Stuart, Murray, The Geology of Oil, Oil Shale, and Coal.
13. Thompson, A. B., Oil-field Exploration and Development.
14. Ziegler, Victor, Popular Oil Geology.

PUBLICATIONS OF TECHNICAL AND SCIENTIFIC ORGANIZATIONS.

1. American Association of Petroleum Geologists; Bulletin.
2. American Institute of Mining and Metallurgical Engineers; Mining and Metallurgy, Transactions, Technical Papers, and Petroleum Development and Technology.
3. Geological Society of America; Journal.
4. Institute of Petroleum Technologists; Transactions.

TECHNICAL JOURNALS AND TRADE PAPERS.

1. Economic Geology.
2. Engineering and Mining Journal.
3. Journal of Geology.
4. National Petroleum News.
5. Mining and Oil Bulletin.
6. Oil and Gas Journal.

7. Oil Engineering and Technology.
8. Oilfield Engineering.
9. Oil Trade Journal.
10. Oil Weekly.
11. Petroleum Times.
12. Petroleum World.
13. Petroleum Zeitschrift.

Much valuable information is also contained in the reports of state and national geological surveys and similar public organizations. Sometimes these are issued regularly. Thus, ''California Oil Fields,'' the report of the state oil and gas supervisor of California is issued monthly. More frequently, the reports are issued at irregular intervals as individual bulletins. An increasing amount of such material is being issued in mimeograph form as press notices with the expectation that it will be printed by the various trade journals. The student will find the various publications of the U. S. Geological Survey and Bureau of Mines to contain a large amount of valuable reference material.

CHAPTER II.

SOME PROPERTIES OF PETROLEUM.

Petroleum is a mixture of varying proportions of different chemical compounds. The physical and chemical properties of each individual oil depend upon the nature and amount of the several compounds present in that oil. The most prominent group of compounds present in all oils is the hydrocarbon family. As the name indicates, these are composed solely of hydrogen and carbon. Within the group are a number of subgroups and an unknown number of individual compounds differing from one another in physical and chemical properties. Some are normally gaseous, others are liquids, still others are solids. The liquids naturally predominate in petroleums; the gaseous, in natural gas. The solids are important in asphalt, ozokerite or mineral wax, and related bitumens. Gaseous and solid constituents may be dissolved in liquid petroleums. Easily volatilized compounds, which are normally liquids, are frequently contained in gases. Even the hardest asphalt will exude a little liquid matter on sweating.

The subgroups have many properties in common but differences between them are of importance in determining the value of oils from the standpoint of the refiner. Within the subgroups the chemical properties of the various compounds are much the same; but they vary considerably in density, viscosity, volatility, and other physical properties. Within the same group compounds may be gases, liquids, or solids at normal temperatures.

In addition to the true hydrocarbons, most crude oils contain some sulphur, oxygen, or nitrogen containing compounds. In the majority of the cases, these elements are chemically combined with hydrogen and carbon, and are known as sulphur, oxygen or nitrogen-bearing hydrocarbons. Hydrogen sulphide and elemental sulphur are not infrequently dissolved in petroleum. Similarly, small quantities of nitrogen, oxygen, and water are of frequent occurrence.

In some cases the sulphur, oxygen, and nitrogen may be considered as indigenous to the oil containing them. In others they were certainly of later introduction. Earthy matter is commonly brought to the surface with oil. Most of this is probably held in temporary suspension but some would appear to be in a colloidal state, if not actually dissolved in the oil. Analyses are seldom made to include the amount and nature of such matter; but small amounts of vanadium, nickel, phosphorus, and other elements have been found in some oils. The variety of compounds and elements present in natural gas is much less than in that of the liquids. However, carbon monoxide, carbon dioxide, hydrogen sulphide, free hydrogen, oxygen, nitrogen, and inert gases, such as helium, have been found to occur with the hydrocarbons. The brines associated with petroleum and natural gas in their natural reservoirs contain an infinite variety of dissolved compounds.

The physical properties of crude oils and of refinery products produced from them naturally depend upon the sum of the properties of the compounds of which they are composed. Thus individual oils show great difference in color, density, viscosity, and other physical properties.

Color.—Crude oils vary in color; some are practically colorless, others are pitch black. The highly prized crude oils of West Virginia, New York, and Pennsylvania are largely of amber color. Green is probably the predominating color of medium gravity oils throughout the world. Heavy types, such as those of Mexico, California, and Venezuela, are commonly black. Some may have a greenish or brownish cast. The natural kerosenes and gasolines found occasionally in drilling in central New York State, parts of Cuba, and other areas, are almost colorless. They are of no commercial importance. With the exception of the very light oils produced in the San Juan Basin of northwestern New Mexico, those that are lighter in color than amber are of little commercial value because of the small yield of wells where they are found. Color in oils is frequently, although not always, an indication of value. It depends upon the presence of unsaturated compounds of the hydrocarbon type and various nitrogen, sulphur, and oxygen containing compounds.

Oils of mineral origin have a distinct bloom or fluorescence when observed by reflected light. Because of this most oils thus viewed have a greenish cast. As the quality of fluorescence is not shown by animal and vegetable oils, this serves as a quick method of determining the origin of an oil, whether mineral or organic.

Odor.—To a large extent the compounds responsible for the color of oils are also responsible for differences in their odors. The "gasoline" odor is typical of Pennsylvania, light Oklahoma, and other crude oils which contain large amounts of volatile hydrocarbons and relatively small amounts of unsaturated, sulphur, or nitrogen containing compounds. The pungent odor of the aromatic compound is prominent in East Indian, Russian, and some California crudes. The nauseating odor of hydrogen sulphide characterizes the high sulphur crudes of Mexico, Trinidad, and Venezuela. The odor is slightly less distinct in the oils of the Lima-Indiana and Petrolia (Ontario) districts, which contain somewhat less sulphur and different types of sulphur compounds.

Density.—The density of petroleum is expressed either in terms of specific gravity using water as the base, or on the empirical Baume scale derived from it. The first is found by dividing the weight of a unit volume of oil by the weight of the same volume of distilled water at 60° F. temperature. The result, as oils are lighter than water, is always a fraction or a decimal. Differences in specific gravity are not large even though the oils are of very different chemical character. Because of this, readings to the second and third decimal places were necessary to indicate slight differences in gravity, which are of major importance to the refiner. In determining the density of liquids, the hydrometer method is the most satisfactory. The markings of the specific gravity hydrometer are not equidistant. As a result the empirical Baume scale, which uses whole numbers to bring out differences and equally spaced markings on the hydrometer, has largely displaced the specific gravity scale in the oil industry. The true Baume scale, also called the Bureau of Standards Scale in the United States, has a modulus of 140. Its relation to the specific gravity scale may be determined from the following formulas:

$$\text{Degrees Baume} = \frac{140}{\text{Specific Gravity } 60^\circ/60^\circ \text{ F.}} - 130$$

$$\text{Specific Gravity } 60^\circ/60^\circ \text{ F.} = \frac{140}{130 + \text{Degrees Baume}}$$

The scale commonly used in the oil industry, and especially in the United States, is not the true Baume scale but has a modulus of 141.5. This scale has recently been made standard for trade usage and is referred to as the American Petroleum Institute scale or A.P.I. scale. All readings now made by oil companies and governmental bureaus in the United States are based on this scale. Older readings were partly based upon this and partly upon the 140 modulus scale. The A.P.I., or A.P.I. Baume scale reading may be converted into a specific gravity decimal in the same way as the true Baume reading is; but the formula differs somewhat:

$$\text{Degrees A.P.I.} = \frac{141.5}{\text{Specific Gravity } 60°/60° \text{ F.}} - 131.5$$

$$\text{Specific Gravity} = \frac{141.5}{\text{Degrees A.P.I.} + 131.5}$$

Differences between readings on the A.P.I. and the true Baume scales are too slight to be of importance when crude oils and heavy fractions are being compared, but should be taken into consideration when comparing the light gasoline and benzine fractions.

The heaviest crude oils now being produced in any quantity come from the Panuco district of Mexico, where oils of from slightly more than 10° Baume to 12 and 13° Baume are obtained. The light oil of the southern or Tuxpam district averages between 20 and 25° Baume. Mene Grande, Venezuela, produces some 16° Baume oil. Much of that of Argentina, California, South Texas, Trinidad, Baku (Russia), and Borneo, is of the same type as the light Mexican and Venezuelan crudes mentioned.

Table 3.—Comparison of Gravity Scales.

Specific Gravity at 60° F.	Baume Gravity B. of S. Modulus	Baume Gravity A.P.I. Modulus	Specific Gravity at 60° F.	Baume Gravity B. of S. Modulus	Baume Gravity A.P.I. Modulus
1.0000	10.0°	10.0°	.7368	60.0°	60.5°
.9655	15.0	15.1	.7179	65.0	65.6
.9333	20.0	20.1	.7000	70.0	70.6
.9032	25.0	25.2	.6829	75.0	75.7
.8750	30.0	30.2	.6667	80.0	80.7
.8485	35.0	35.3	.6512	85.0	85.8
.8235	40.0	40.3	.6364	90.0	90.8
.8000	45.0	45.4	.6222	95.0	95.9
.7778	50.0	50.4	.6087	100.0	100.9
.7568	55.0	55.5			

The so-called light oils of California average between 28 and 35° Baume. The Infantas pool of Colombia, the Mendoza-Neuquen area of Argentine, and the Maidan-I-Naftun pool of Persia produce oil of the same general character. With the exception of the recent deep sand developments, the oils of the Mid-Continent province of the United States average between 32 and 40° Baume. Similar oils are prominent in Wyoming, Illinois, Ohio, Ontario, and Kentucky. Practically all of the oil obtained in West Virginia, New York, and Pennsylvania is between 40 and 45° Baume. Several of the deep sand pools of Oklahoma produce 45° Baume oil, and Cat Creek, Montana, yields one of 49° Baume. Crudes lighter than this are so uncommon as to be classed as freak oils. However, substantial amounts of oil of 61° Baume gravity have been secured in the Hogback and Rattlesnake domes in the San Juan Basin of New Mexico.

Viscosity.—The viscosity of oils is the measure of their resistance to flow. It decreases in all oils with increase in temperature. In general, viscosities vary directly with the density of oils. Thus the heavy Panuco oils require heating before they can be pumped. The same is true of some of the California and East Indian crudes. Light oils, such as those of the Appalachian area, are only slightly more viscous than water at normal temperatures. In winter their viscosity rises with the congealing of the dissolved wax. Congealing of wax is extremely important in the medium gravity oils of the Panhandle area of northwest Texas. Here movement of oil through pipes in winter presents a serious problem.

Viscosity measurements and comparisons are important in determining the lubricating value of oils and the ease with which they may be transported. Differences in viscosity of individual compounds may have been of major importance in determining the present character of crude oils contained in the earth's crust. Nevertheless, the methods of measuring viscosity are far from ideal. All of the instruments in use depend upon the measurement of the time taken for a given quantity of oil to flow through a small opening. The size of the opening and the manner of causing the oil to flow through it are defined for each instrument. Usually the oil flows by gravity. The instruments in common use in the United States are the Saybolt Universal and Furol viscosimeters; and in Europe, the Redwood, and Engler viscosimeters.

The viscosities of a number of representative crude oils from North and South America as determined by the United States Bureau of Mines are given in Table 4. The gravity according to the A.P.I. modification of the Baume scale is also shown. The general relationship between gravity and viscosity is indicated, but abnormal viscosities are also shown.

Table 4.—Viscosities of Typical Crude Oils.*

Source	A.P.I. Gravity	Saybolt Universal Viscosity	
		At 70° F.	At 100° F.
Mexico, Cerro Azul	21°	1700 seconds	634 seconds
Mexico, Zurita	12.3	over 6000	over 6000
Trinidad, Morne L'Enfer Reserve	16.2	4120	1220
Argentine, Comodoro Rivadavia	20.	over 6000	2490
Venezuéla, Mene Grande	16.	4550	1370
Colombia, Infantas	28.8	144	89
Peru, Lobitos	36.8	41	38
Wyoming, Osage	37.6	102	62
Oklahoma, Garber	45.6	35	34
Oklahoma, Cushing	39.8	47	37
Ohio, South Lima	36.6	55	46
California, Lost Hills	18.4	1275	500
Pennsylvania, Kean County	40.4	47	41
Louisiana, Vinton	19.7	880	310

* Analyses by U. S. Bureau of Mines.

Coefficient of Expansion.—The tendency of oils to expand with increasing temperatures and to contract with decreasing ones has long been recognized. Allowances for expansion and contraction are made

Table 5.—Coefficients of Expansion for Oils of Different Gravities at 60° F.*

Specific Gravity at 60° F.	Change in Sp. Gr. for 1° F.	Specific Gravity at 60° F.	Change in Sp. Gr. for 1° F.
0.63	0.00053	0.79	0.00040
0.64	52	0.80	39
0.65	52	0.81	39
0.66	51	0.82	39
0.67	50	0.83	38
0.68	50	0.84	37
0.69	49	0.85	37
0.70	49	0.86	37
0.71	48	0.87	37
0.72	47	0.88	36
0.73	46	0.89	36
0.74	45	0.90	36
0.75	44	0.91	36
0.76	43	0.92	36
0.77	42	0.93	36
0.78	41		

* Anderson, J.: Ind. Eng. Chem., 12, p. 1011, 1920.

in the sale of oils in quantity. The coefficient of expansion varies with different oils. In general it is less in oils of high density than in those of low density. The differences in the coefficients of expansion for oils of different gravities, as determined by the United States Bureau of Standards, are given in Table 5.

It is also indicated that the coefficient of expansion is not the same for the same oils at different temperatures but decreases with rising temperatures. The following table is given by Bell to show the difference in the rate of expansion of a Galician petroleum at different temperatures.

TABLE 6.—COEFFICIENT OF EXPANSION AT DIFFERENT TEMPERATURES FOR GALICIAN PETROLEUM.*

Temperature in Degrees C.	Coefficient of Expansion per Degree C.
1	0.001095
10	0.001103
20	0.0009643
30	0.0008587
40	0.0008505

* Bell, H. S.: American Petroleum Refining, p. 44, 1923.

Volatility.—The boiling point of methane, the most prominent constituent of natural gas, is —164° C. That of normal pentane, an important constituent of gasoline, is 36.3° C. From these the boiling points of the normal paraffin compounds which have been ascertained run up to 331° C. for pentatriacontane ($C_{35}H_{72}$). The range in other families is similar. It is therefore impossible to speak of the boiling point of a crude oil, which is a complex mixture of many different hydrocarbons. Furthermore it would appear that a very large proportion of the hydrocarbons present in crude oils do not have true boiling points but decompose or "crack" before they are vaporized. This is of extreme importance in the refining of the heavy lubricating fractions of paraffin base oils. Here many undesirable constituents cannot be removed by fractional distillation without destroying the value of the lubricant by the intense heat used. The absence of a true boiling point is equally important to the geologist in considering the value of theories of the origin of oil involving distillation of the oil or of its parent substances.

Solidification.—Many compounds contained in petroleum appear to have definite melting points. This is certainly true of the members of the paraffin series. Even the gas methane becomes a solid at the temperature of —184° C., or 20 degrees lower than its boiling point.

In the more complex compounds of the unsaturated types, there may not be a sharp point of demarcation between the liquid and the solid states. Crude oils, as distinct from individual compounds, cannot be said to have definite solidification points. Viscosity increases rapidly as zero temperatures are approached, and ultimately all oils pass into a state where they are too viscous to permit measurements of their viscosities in the ordinary manner.

At that point they may be said to have passed from the true liquid state into the condition of plastic solids. If the chilling be continued still further, the solid state is finally reached. The exact nature of the process of solidification in crude oils is difficult to explain because of the known presence of dissolved solids, which tend to congeal ahead of the liquid parts. The large percentages of asphaltic constituents present in Mexican crudes and similar types make it impossible to pour these oils at even moderately cool temperatures. The wax contained in Pennsylvanian oils separates out to cause cloudiness at high temperatures and prevent pouring of the oils at low ones. Yet the bulk of both types of oils is composed of ingredients that can be poured individually without difficulty at temperatures considerably lower than those at which the oil itself can no longer be poured. The general absence of any relationship between pour point (the lowest temperature at which pouring is possible) and density is indicated by the following:

TABLE 7.—POUR POINTS OF TYPICAL CRUDE OILS.*

Source	A.P.I. Gravity	Pour Point in Degrees F.
Mexico, Chapapote Nunez	24.0°	50° F.
Mexico, Toteco	20.8	10
Mexico, Topila	17.1	40
Trinidad, Tabaquite	41.7	below 5
Trinidad, Morne L'Enfer	16.5	below 5
West Virginia, Kelly Creek	45.2	32
West Virginia, Harrison and Doddridge	42.3	57
West Virginia, Cabin Creek	45.7	below 5
Pennsylvania, Alleghany	45.0	below 5
Pennsylvania, Green Co.	41.8	25

* Analyses by U. S. Bureau of Mines.

Surface Tension and Capillary Action.—The free surface of a liquid behaves much like an elastic membrane, the individual molecules having a definite attraction for one another. The force needed to pull apart adjacent portions of such surfaces may be measured. It differs considerably in different liquids. The measure of the force in any liquid is known as the surface tension of that liquid. When the free surface of a liquid is confined to a very small area, such as a capillary tube, the liquid surface is also acted upon by the force of adsorption, the attraction of the surface of solid matter composing the wall of the tube for the liquid. Adsorption and surface tension tend to bring about the phenomenon called capillarity. Thus, any liquid, that wets the tube wall because of the mutual attraction of the wall material and the molecules of the liquid, will tend to rise in that tube until the weight of the column of liquid below the capillary surfaces balances the vertical component of the liquid's surface tension. The amount of the vertical component is determined by the angle of capillarity made by the liquid surface and the tube wall. This varies with the nature of the liquid and the nature of the tube. The force of capillarity rises with decrease in diameter of the tube. The tendency of liquids to rise in capillary tubes is materially lessened by decrease in their surface tensions, with increasing temperatures.

TABLE 8.—SURFACE TENSIONS AND CAPILLARY CONSTANTS OF TYPICAL CRUDE OILS.*

Source	Specific Gravity at 15° C.	Surface Tension in Dynes per Centimeter	Capillary Constant
Pennsylvania	.799	24.07	6.17
Pennsylvania	.800	25.12	6.44
Pennsylvania	.808	24.81	6.30
Pennsylvania	.816	25.44	6.38
Oklahoma	.825	24.78	6.15
Oklahoma	.838	26.19	6.40
Oklahoma	.846	25.03	6.06
Healdton	.865	26.59	6.30
Oklahoma	.870	26.59	6.26
California	.876	25.70	6.00
Russia	.876	27.55	6.43
Russia	.878	27.82	6.49
California	.891	26.08	5.99
S. Maria	.901	26.13	5.94

* After Rittman, W., and Egloff, J.: Ind. Eng. Chem., Vol. 7, p. 578, 1915.

Note. The surface tension measurements were made by the use of the Morgan drop method. Values for the capillary constant were obtained from the formula:

$$\text{Capillary constant} = \frac{2 \times \text{surface tension}}{9.8 \times \text{specific gravity}}$$

The importance of differences in surface tension upon the migration of oil, gas and water, and upon their retention in sands and other porous reservoir rocks cannot be over-stressed. The surface tension of a water-air surface is about 72.8 dynes at 20° C.; that of ordinary oils is only about one third as much. While allowance must be made for the slightly greater density of water, the force available to bring about capillary movement in water is seen to be materially greater than that for oils. It follows that the water may be expected to draw itself into the finest pore spaces of a rock and to force the oil into the larger pores.

In general the surface tensions of oils vary with their density, but this is not always true. The ability of liquids to enter and maintain themselves in minute pores and openings is called the capillary constant. As it is a function of both gravity and surface tension, it does not necessarily vary directly with surface tension.

Optical Activity.—Petroleum is said to be optically active; that is, it has the power of rotating the so-called plane of polarized light. Such rays, vibrating only in one plane, are strongly influenced by many organic solutions and liquids. Some cause the light to rotate to the left, others cause it to rotate to the right. Practically all petroleums are optically active. Such activity is considered as being due to the presence of cholesterin, or phytosterin, or their derivatives. The importance of this in determining the origin of oils may be inferred from the fact that these two compounds are found in organic matter, the first being of animal origin, the second of vegetable origin.

Other Physical Properties.—Other properties of petroleum and of its refined products, such as flash and burning points, calorific values, latent heats of vaporization, and specific heats, are of great importance to the refiner and the consumer. They do not so directly interest the geologist.

Chemical Composition.—The complexity of the composition of petroleum and the instability of many of its compounds make it impossible for the chemist to isolate and study every individual compound. While investigators have done considerable in this line, the compounds that have been studied are largely those found in the lighter and more volatile fractions of the crude oil. These are compounds that are highly desirable from the standpoint of commercial value because of their stability. Much remains to be learned about the chemical and physical properties of the unstable, heavy and nonvolatile compounds, which make up a large part of all oils and predominate in the heavy types.

The wide difference in the properties of different compounds present in petroleum, other than those caused by the presence of sulphur, oxygen, and nitrogen, may be traced directly to the unusual qualities possessed by the carbon atom. Carbon atoms are called quadrivalent atoms; that is, they have the power of combining with four atoms of a univalent element. Thus, four atoms of the univalent element hydrogen will combine with one of carbon to form the gas methane. No known compound of carbon and hydrogen contains more than four units of hydrogen to one of carbon. However, all except methane contain less than that ratio. The explanation of this lies in the fact that carbon atoms have the power of uniting with one another. Thus the number of possible combinations between carbon and hydrogen atoms becomes almost unlimited.

Hydrocarbons.—The basic grouping of true hydrocarbons has two divisions: one, having the carbon atoms linked to each other in the form of a chain similar to the links of an anchor chain; the other, having the atoms linked in the endless circle or ring of the bracelet. The first group is known as the open chain, straight chain, or alipathic group; the second is called the closed chain, ring chain, or aromatic type.

It is customary to place methane in the first group; but more properly it should be placed alone, as it is neither chain nor ring. Methane is the only hydrocarbon in which all of the valences of the carbon atom are linked with atoms of hydrogen. Strictly speaking it is the only compound in which the carbon atom is "saturated" with hydrogen. As the degree of saturation determines the stability of hydrocarbons from the chemical standpoint, methane is the most stable compound known. Those that resemble it most closely in this respect are the hydrocarbons in which the percentage of hydrogen present is such as to make it necessary for the carbon atoms to link with the adjacent carbon atoms by one bond only. To these the name "saturated" is now commonly applied.

In the alipathic group, this includes all of the compounds of the methane or paraffin series. In the ring chain type, it may be used in referring to the naphthene family. All other series of compounds contain two or more atoms of carbon linked to each other by two or even three valences and are referred to as unsaturated. Strict usage limits the terms saturated and unsaturated to series within the alipathic or open chain group, but the application to the ring types seems to be justified. The more prominent series of hydrocarbons recognized as being present in petroleum are listed.

TABLE 9.—CLASSIFICATION OF HYDROCARBONS.

Group	Division	Name	Basic Formula
Open chain....	Saturated	Paraffin or Methane	C_nH_{2n+2}
Open chain....	Unsaturated	Olefine or Ethylene	C_nH_{2n}
Open chain....	Unsaturated	Acetylene	C_nH_{2n-2}
Open chain....	Unsaturated	Diolefine	C_nH_{2n-2}
Open chain....	Unsaturated	Olefineacetylene	C_nH_{2n-4}
Open chain....	Unsaturated	Olefine terpene	C_nH_{2n-4}
Open chain....	Unsaturated	Triolefine	C_nH_{2n-6}
Ring..........	Saturated	Naphthene	C_nH_{2n-6+6}
Ring..........	Unsaturated	Benzene	C_nH_{2n-6}
?	Unsaturated	Naphthalene, Anthracene, and other series, probably main ring types	C_nH_{2n-8} to C_nH_{2n-20}

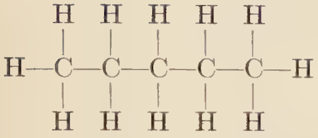
Paraffin Series.—Paraffin hydrocarbons are lighter than those compounds of the other series which approach them most closely in composition. The lower members of the series are gases, or liquids of low boiling point. Some of the solids melt at comparatively low temperatures and can be vaporized in the vacuum still, or in the presence of steam, without difficulty. Many of the higher members, while liquids at normal temperatures, are subject to decomposition before their boiling points, if they have true boiling points, can be reached even in the vacuum still. Compounds of this family are more stable chemically than those of the others. They do not react with acids or alkalines to any great extent; they are not attacked by oxidizing agents and are insoluble in water.

Isomeric Compounds.—The table of paraffin compounds given includes only the compounds of the normal type. In addition to these, there are an unknown number of other compounds differing from the normal in physical and chemical properties because of differences in internal structure. While preserving the principle of the open chain and the general characteristics of the family, they deviate from the normal types in some respects. The structural diagrams for the three pentanes, normal, iso, and neo or tertiary, are shown to indicate the assumed internal differences. The different compounds differ in physical properties sufficiently to give the impression of wholly different compositions. In the higher members of the paraffin and other series, the number of possible variations from the normal is greatly increased.

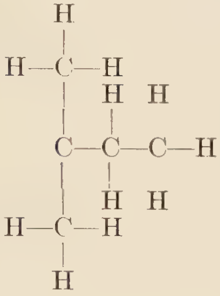
TABLE 10.—PROPERTIES OF NORMAL, ISO, AND NEO PENTANE.*

	Composition	Sp. Gr.	Melting Point	Boiling Point
Normal	C_5H_{12}	0.6454	—130.8° C.	36.3° C.
Iso	C_5H_{12}	0.6393	——	30.4
Neo	C_5H_{12}	——	— 20.	9.

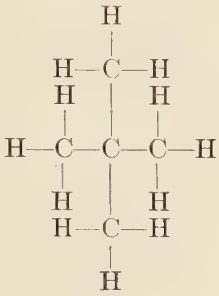
Normal Pentane



Iso-Pentane



Tertiary or Neo Pentane



* After Bell, H. S.: American Petroleum Refining, pp. 14, 16, 17, 1923.

The paraffin family contributes the bulk of the combustible matter of natural gases all over the world. Its liquid members, together with dissolved solids of the same family, form the major part of the paraffin base oils produced in the Appalachian field. They are present in large amounts in the medium density oils of Oklahoma, Kansas, Peru, Galicia, Burma, and other areas. Small proportions of them are present even in the heavy crudes produced in Mexico.

Olefine Series.—The true olefine or ethylene series is similar to the paraffin series except that two adjacent carbon atoms are joined by a double link. The members of the series are slightly heavier than corresponding members of the paraffin family. These compounds, while fairly stable, react with sulphuric acid and are readily attacked by oxidizing agents. While of frequent occurrence, they are by no means as prominent in petroleum as the paraffins or the naphthenes.

Other Alipathic Compounds.—The acetylene series, in which two carbon atoms are linked together by three valences, is not a common series in petroleum. The diolefines series, of the same composition but differing in having two double bonds instead of the single triple one of the acetylenes, is found in many crude oils. It is also produced in large amounts in the cracking still. Diolefines are generally unstable and are readily attacked by acids and oxidizing agents. The qualities of the higher chain series are largely similar to those of the diolefines. Many decompose so readily that the study of their properties is practically impossible. Because of this instability, and the discoloration and poor burning qualities of the products containing such compounds, they are extremely obnoxious to the refiner.

TABLE 11.—PROPERTIES OF NORMAL PARAFFINS.*

Name	Formula	Specific Gravity	Melting Point	Boiling Point
Methane.........	CH_4	.415	−184° C.	−164° C.
Ethane..........	C_2H_6	.446	−172.1	− 84.1
Propane.........	C_3H_8	.536	——	− 37.
Butane..........	C_4H_{10}	.600	−135.3	1.
Pentane..........	C_5H_{12}	.6454	−130.8	36.3
Hexane..........	C_6H_{14}	.6603	− 94.03	68.9
Heptane (Neo)....	C_7H_{16}	.70186	− 97.1	98.3
Octane...........	C_8H_{18}	.7188	——	125.8
Nonane..........	C_9H_{20}	.7177	− 51.	150.8
Decane..........	$C_{10}H_{22}$	.7467	− 31.	173.
Endecane........	$C_{11}H_{24}$	.7581	− 26.5	196–197.
Dodecane........	$C_{12}H_{26}$	.7676	− 12.	214–216.
Tridecane........	$C_{13}H_{28}$	.775 at melting point	− 6.	234.
Tetradecane......	$C_{14}H_{30}$	.775 "	4.	252.
Pentradecane.....	$C_{15}H_{32}$	.776 "	10.	270.
Hexadecane......	$C_{16}H_{34}$	.775 "	18.	287.
Heptadecane......	$C_{17}H_{36}$	.777 "	22.	303.
Octadecane.......	$C_{18}H_{38}$	.777 "	28.	317.
Nonadecane......	$C_{19}H_{40}$	.777 "	32.	330.
Eicosane.........	$C_{20}H_{42}$	.778 "	37.	205. at 15 mm. of pressure.
Heneicosane......	$C_{21}H_{44}$	.778 "	40.	215. "
Docosane........	$C_{22}H_{46}$	.778 "	44.	224. "
Tricosane........	$C_{23}H_{48}$	.779 "	48.	234. "
Tetracosane......	$C_{24}H_{50}$	.779 "	51.	243. "
Pentracosane.....	$C_{25}H_{52}$	——	53.5	——
Hexacosane.......	$C_{26}H_{54}$	——	58.	——
Heptacosane......	$C_{27}H_{56}$	.780 "	60.	270. "
Octacosane.......	$C_{28}H_{58}$	——	60.	——
Nonacosane......	$C_{29}H_{60}$	——	62.5	——
Hentriacontane...	$C_{31}H_{64}$	.781 "	68.	302. "
Dotriacontane....	$C_{32}H_{66}$	.781 "	70.	310. "
Tetratriacontane..	$C_{34}H_{70}$	——	71.5	——
Pentatriacontane..	$C_{35}H_{72}$	——	75.	——
Dimiicyl.........	$C_{60}H_{122}$	——	102.	——

* Adapted from Engler-Höfer: Meyer and Jacobson, Lehr. d. org. Chem., 2d Ed., I.

Naphthene Series.—The naphthene series of hydrocarbons resembles the paraffins closely in physical and chemical properties except density. The compounds are much heavier than those of the paraffin series and than their isomers, the olefine compounds. They are slightly less stable than the paraffins, but distinctly more stable than the olefines. Naphthene compounds are present only in relatively small amounts in Pennsylvanian and other light oils, but form a large part of Russian, Californian, East Indian, and other heavy crudes. Like the paraffins, they occur in many of the mixed base crude oils of medium gravity. The properties of a few of the more prominent normal low-boiling point members of this series are shown in Table 12.

TABLE 12.—PROPERTIES OF TYPICAL NAPHTHENES.*

Name	Formula	Melting Point	Boiling Point	Specific Gravity
Cyclopropane	C_3H_6	−126° C.	−35° C.	———
Cyclobutane	C_4H_8	− 80.	11–12	.0738 at 0° C.
Cyclo pentane	C_5H_{10}	− 80.	50	.7635 at 0° C.
Cyclo hexane	C_6H_{12}	6.4	80.8 to 80.9	.7788 at 19.5° C.
Cyclo heptane	C_7H_{14}	———	117 to 117.5 at 763 mm.	.816 at 15° C.
Cyclo octane	C_8H_{16}	11.5	147.3 to 148.3	.850 at 0° C.
Cyclo nonane	C_9H_{18}	———	170–172	.7722 at 16° C.

* Adapted from Engler-Höfer: Skowronski-Metan, 61, 73, 86, 97, 109, 1918.

Benzene Series.—The benzene series is built around a central ring which contains six carbons alternately joined by single and double bonds. From this, by replacement of the hydrogens joined to the carbon atoms by the radicle CH_3, a large number of compounds of varying properties is possible. They are fairly stable compounds but are attacked by concentrated sulphuric acid. The most prominent members of this series are benzene, toluene, and xylene. The first two have no isomers but the xylenes and higher compounds have. Benzene compounds are probably present in a large number of crude oils in small amounts. The percentage in the lighter oils is insignificant but the amount in some Californian, Persian, and East Indian crudes is believed to be fairly substantial. The properties of some of the members of the series are given in Table 13.

TABLE 13.—PROPERTIES OF TYPICAL BENZENE COMPOUNDS.*

Name	Formula	Specific Gravity	Melting Point	Boiling Point
Benzene	C_6H_6	.8785	5.4° C.	80.4° C.
Toluene	C_7H_8	.869 at 16° C.	97–99.	110.3
Ortho xylene	C_8H_{10}	.880	−28.	142.
Meta xylene	C_8H_{10}	.881 at 0° C.	−53.	138.9
Para xylene	C_8H_{10}	.880 at 0° C.	3.	138.
Mesitylene	C_9H_{12}	.865 at 14° C.	−57.5	164.5
O. cymene	$C_{10}H_{14}$	.876	−73.5	175–176.
Durol	$C_{10}H_{14}$	.901	−79.	203–204.

* Adapted from Engler-Höfer: K. von Auwers Ann., 419, 92–120, 1919.

Other Ring Compounds.—Very little is definitely known of the other series of ring compounds, although it is probable that they form a large part of the non-volatile portions of heavy crude oils. Members of the naphthalene series have been identified in California and Borneo crudes. They differ from the naphthene and benzene compounds in having a double ring center instead of a single ring. Similarly anthracene compounds have been isolated from Russian oils. The boiling points of most naphthalene, anthracene and other higher ring types of compounds are high. Their study and identification is therefore difficult. They are heavier than the common open chain compounds and the members of the naphthene and benzene series. A few are probably heavier than water. They are so slightly known that little can be said of their importance. Their presence in relatively young oils and their apparent absence in the bulk of the oils of Paleozoic age present an interesting geological problem.

Sulphur Compounds.—Next to carbon and hydrogen, sulphur is the most prominent element in crude oils. Some sulphur is distributed throughout petroleums in the form of elemental sulphur. A considerable amount is present in the form of dissolved hydrogen sulphide gas. This is also present in natural gases. The bulk of the sulphur in most oils is probably present in the form of organic compounds. Some of these contain oxygen as well as sulphur, hydrogen, and carbon. The sulphur containing hydrocarbons present a serious problem to the refiner and have been studied by many chemists. There appear to be at least six different series of these compounds: the thiophenes, thiopanes, sulphones, alkyl sulphides, mercaptans or alkyl hydrosulphides, and the alkyl sulphates.

Some of the compounds are unstable and polymerize readily on standing. Others are chemically inactive and are not affected by the ordinary acids and alkalines used in the refinery. Sulphur compounds are uniformly heavy. Most of the heavier types of oils contain large percentages of sulphur. However, the density of oils cannot be said to depend upon their sulphur content exclusively. Many of the heavier types contain only small percentages and owe their high densities to the presence of benzene, naphthalene, and other series of heavy ring compounds. The majority of the sulphur compounds have high boiling points, but a number are as volatile as the lower members of the naphthene and paraffin series. Sulphur compounds, in addition to increasing the density of oils, increase their viscosity. The sulphur percentages of some typical oils are given in Table 14.

Table 14.—Sulphur Contents of Typical Crude Oils.*

Source	Percentage of Sulphur	A.P.I. Gravity
Ontario, Rothwell	1.05%	35.6°
Mexico, Cerro Azul	3.61	20.8
Mexico, Topila	4.55	17.1
Trinidad, Morne L'Enfer	1.81	16.5
Argentine, Comodoro Rivadavia	0.17	20.8
Venezuela, Mene Grande	2.65	16.
Montana, Kevin-Sunburst	0.96	24.
Wyoming, Osage	0.29	37.6
West Virginia, Cabin Creek	0.19	45.7
California, Sunset-Midway	1.16	12.7

* Analyses from U. S. Bureau of Mines.

Oxygen Compounds.—Free oxygen is found in small amounts in petroleum. The bulk is contained in fatty acids, naphthenic acids, phenols, and similar compounds in combination with hydrogen and carbon. While it is believed that the oxygen content of many crude oils is between two and three percent—an amount somewhat greater than the average sulphur percentage—less is known about oxygen compounds because of their relatively high boiling points. Like sulphur compounds, they increase the viscosity of oils considerably. Similarly they add materially to the density.

Nitrogen Compounds.—Free dissolved nitrogen is found in oils and natural gases in variable amounts. Combined nitrogen, present in the form of quinolines and related compounds, probably occurs in most petroleums. The amount is generally insignificant. In California and Japanese crude oils, the amount is large. Mabery[1] places the percentage of quinolines in some California oils as high as from 10 to 20%. The amount of nitrogen present in the individual quinoline compound is so small that the nitrogen content of the oil is seldom more than one percent of the volume. Nitrogen compounds are known for their pungent odor, high specific gravity, and chemical instability. Their presence is important in discussions on the origin of oils.

---

[1] Mabery, Charles: Jour. Soc. Chem. Ind., Vol. 19, p. 505, 1900.

Other Ingredients in Petroleum.—Minor amounts of other elements have been identified in petroleum. Much importance has been attached by those supporting inorganic theories of the origin of oil to the identification of nickel and vanadium in petroleum. The nature of the compounds containing these elements is not known. Until recently the existence of phosphorus in petroleum was not definitely proved, but Palmer[1] reports the occurrence of this element to the amount of 1/100 of 1% in oil from the Kern River district of California.

The Base of Oils.—While no individual oil can be said to be composed entirely of compounds of one family, it is customary to place oils in definite groups, the group being determined by the family of the most prominent type of compounds present. As most oils are composed largely of paraffin or naphthene base compounds, it follows that oils are commonly divided into paraffin base and naphthene base types. Between the two are a group of oils containing so large a percentage of both types that neither can be said to predominate over the other. Such oils are called mixed base types. Before the difference between the chemical properties of the several compounds present in oils was fully understood, the trade used the distinctions "paraffin base" and "asphaltic base." The distinction was based upon the fact that paraffin wax and petrolatum were produced in refining the first, and that a semi-solid or solid residue of asphaltic character remained after the lighter products had been distilled off the second. The term paraffin base of the chemist may be considered as synonymous with the expression used by the trade. Practically all crude oils that yield solid waxes also contain large amounts of the liquids of the paraffin family. The waxes are themselves almost exclusively compounds of this group.

While the term asphaltic may usually be applied to the oil with a naphthene base, the terms are not necessarily synonymous. Asphaltic residues, while probably composed in part of solid members of the naphthene family, probably contain larger amounts of heavy unsaturated ring compounds, sulphur-containing hydrocarbons, and oxygen-containing compounds.

---

[1] Palmer, C.: Econ. Geology, Vol. 17, pp. 100–104, 1922.

In general, paraffin base oils are of low density. They usually contain large amounts of gasoline and kerosene, moderate amounts of the higher boiling point fraction called gas oil and the lubricating distillates, and small but important amounts of non-volatile oils. The waxy matter is partly volatile at the temperatures of refinery stills and partly non-volatile. The non-volatile oil, possibly composed largely of isomers of the normal paraffins, contains a minimum of asphaltic matter. The naphthene base oil usually contains relatively small amounts of low boiling point fractions, moderate amounts of gas oil, and relatively large percentages of viscous but volatile lubricating oils. The residue is asphaltic. The percentage of asphaltic matter remaining in the still, and the amount of asphalt or carbon forming compounds distilled with the lubricating fractions, is widely different in different oils produced in the same areas.

A further difficulty to the use of the term asphaltic base, in any but the most general manner, lies in the fact that the asphaltic residue is to a large extent the product of the decomposition of non-volatile, but probably liquid, constituents present in the crude oil. This is brought about by the intense temperatures of the refinery still. The amount of asphalt produced by the refinery from any given oil is subject to wide variation through changing the methods of refining.

TABLE 15.—CONRADSON CARBON RESIDUES OF TYPICAL OILS.*

Source	A.P.I. Gravity	Carbon Residue of Non-Volatile Residuum
Peru, Lobitos	36.8°	7.2%
Venezuela, Mene Grande	16.	19.1
Mexico, Toteco	22.5	22.8
California, McKittrick	15.1	12.0
California, Maricopa Flat	21.5	11.1
Kansas, Rantoul	29.1	18.6
West Virginia, Tyler Co	44.1	1.3
Texas, Petrolia	36.5	10.5
Texas, Damon Mound	21.8	3.1
Texas, Ranger	37.	3.9

* The Conradson carbon residue may be defined as the percentage of solid matter left, when the portion of the oil which remains after distillation has been carried to 300° C. under 40 mm. of pressure, is heated to dryness in a retort without access to air. For method of making test see U. S. Bureau of Mines technical paper number 323. Analyses after U. S. Bureau of Mines.

TABLE 16.—CHARACTERISTICS OF TYPICAL PETROLEUMS OF THE WESTERN HEMISPHERE.*

Source	Gravity		Sulphur %	Viscosity in Sec.		Pour Point	Gasoline % †	Total Volatile % ‡	Carbon Residue of Residuum %
	Sp. Gr.	A.P.I.		At 70° F.	At 100° F.				
California, Lost Hills	.956	16.5	0.85	3400.	525.	Below 5° F.	5.1	50.8	13.2
California, Long Beach	.872	30.8	0.80	78.	58.	20°	29.3	79.4	12.5
Oklahoma, Ponca	.812	42.4	0.18	43.4	35.4	5°	39.1	85.1	5.16
Oklahoma, Healdton	.870	30.9	0.72	95.8	64.2	Below 5°	22.3	67.2	8.99
Ontario, Petrolia	.859	33.2	0.92	100.	68.	Below 5°	22.2	64.9	6.4
Texas, West Columbia	.934	20.0	0.29	700.	251.	5°	2.8	69.7	8.8
Ohio, Lima	.835	37.7	0.55	49.8	42.4	Below 5°	31.0	76.3	6.2
Pennsylvania, Venango Co.	.819	40.9	0.10	48.4	41.8	Below 5°	29.6	75.2	2.1
West Virginia, Cabin Creek	.797	45.7	0.19	39.	36.2	Below 5°	40.5	82.6	1.2
Venezuela, Mene Grande	.959	16.	2.65	4550.	1370.	Below 5°	9.2	44.9	19.1
Trinidad, Fyzabad	.931	20.5	0.95	308.	144.	Below 5°	11.6	64.4	10.2
Peru, Lobitos	.841	36.8	0.12	41.	38.	Below 5°	42.3	83.9	7.2
Mexico, Tierra Blanca	.910	24.	3.08	751.	344.	25°	17.4	52.8	20.4
Mexico, Gonzalo	.989	11.6	5.29	over 6000.	over 6000.	40°	7.6	36.6	24.1
Colombia, Infantas	.874	30.4	0.69	101.	68.	Below 5°	23.9	65.6	9.4
Argentine, Comodoro Rivadavia	.929	20.8	0.17	over 6000.	2490.	15°	4.9	38.7	10.5

* Adapted from Analyses of the United States Bureau of Mines.

† Gasoline percentage equals amount distilled under normal pressure up to 200° C.

‡ Total Volatile equals percentage distilled under normal pressure and that distilled up to 300° C. under 40 mm. pressure.

Gravity is generally considered a good key to the base of the oil, light oils being largely of paraffin character, while heavier ones are of naphthene base or contain large amounts of asphalt forming matter. The percentage of asphalt contained in light oils is uniformly low. The percentage contained in the heavier oils is extremely variable. This is indicated by the comparison of gravities and Conradson carbon residues of the non-volatile portions of representative oils given in Table 15. The carbon residue determinations were made by the Bureau of Mines and are probably the best indication of the asphalt forming tendencies of oils we have.

CHAPTER III.

MINERAL BITUMENS RELATED TO PETROLEUM.

As indicated in the previous chapter, the hydrocarbons and related compounds present in liquid petroleum include a number that are not liquids at ordinary temperatures. If permitted to stand in an open tank or reservoir, the gaseous constituents tend to escape from the oil and pass into the atmosphere. While the proportions of the several compounds present may differ, the compounds escaping from the oil are identical with those present in natural gas. Similarly the solid compounds that remain after the evaporation or distillation of the volatile ones are identical in physical and chemical properties with those present in natural asphalts, asphaltites, ozokerites and related substances. It is logical to expect that substances so closely related in occurrence and in chemical nature should have a common, or at least closely related, origin and history.

If we admit the relationship between petroleums and these substances, we are called upon to admit also a close relationship between liquid petroleum and pyrobitumens, as the latter grade imperceptibly into the asphaltites. The line of connection between the liquid petroleum and the pyrobitumen is not clear, chemical and physical characteristics of the two groups being very different. If the asphalts and asphaltites did not form a definite connecting link, the interrelationship between the two extremes would hardly be recognized.

While the relationship is shown in a somewhat different manner, there is ample proof of the kinship of petroleum and natural gas and kerogen or oil shale. Kerogen reacts only slightly with solvents, such as carbon bisulphide and carbon tetrachloride, in which crude oils, asphalts, asphaltites, and the bituminous matter of tar sands are readily dissolved. The products of the destructive distillation of shales include practically all of these obtained from ordinary crude oils. Kerogen shales are not all of the same type but grade into the torbanites, boghead cannels, true cannels, and ultimately must be considered as related to the true coals.

The student of petroleum geology will recognize that any theory that attempts to explain the development of any one of the substances named without regard to its relationship to the rest is founded upon a very insecure base. The theory that postulates the development of asphalt by inorganic agencies must also be capable of explaining the origin of asphaltic oils in the same way. Before discussing the theories of the origin and alteration of petroleum and of the substances closely allied to it, or attempting to show their importance as indicators of the presence of petroleum to the field geologist, it is necessary that we know something about their properties.

Classification of Bitumens.—The natural division of bituminous substances is resolved into gases, liquids, and solids. The indefinite

Table 17.—Classification of Bituminous and Related Substances.

- Liquids
  - Paraffin base oils
  - Mixed base oils
  - Asphalt base and naphthene base oils
- Gases
  - Natural gas
  - Coal gas or mine gas
  - Marsh gas
- Solids
  - Petroleum bitumens
    - Asphaltic bitumens
      - Viscous liquids
        - Maltha
        - Mineral tar
        - Brea
        - Chapopote
      - Asphalt
      - Vein asphalts or asphaltites
        - Gilsonite or uintaite
        - Glance pitch or Manjak
        - Grahamite
      - Rock asphalts
        - Asphaltic limestones and sandstones
    - Mineral waxes
      - Ozokerite
      - Natural ceresin
      - Paraffin soils, etc.
  - Pyrobitumens
    - Vein pyrobitumens
      - Albertite
      - Wurtzilite or elaterite
      - Impsonite
    - Rock pyrobitumens
      - Bituminous schists, marbles, etc.
  - Kerogen or oil shales
  - Coals
    - Bogheads or torbanites, etc.
    - Cannels
    - Normal coals
      - Peats
      - Lignitic coals
      - Bituminous coals
      - Anthracites
      - Graphitic anthracites

character of the classification is evident immediately. On the one side, we find as a transition product between the true liquid and the true gas the substance, casinghead or natural gas gasoline; on the other, viscous substances, such as maltha and chapopote, which cannot be classed either as true solids or true liquids.

The natural solids may for our purposes be divided best into groups according to the closeness of their relationship to petroleum. Those most closely related to petroleum are known as petroleum bitumens. Those in which the relationship to the petroleum bitumens is distinct, but the connection with the liquid petroleum not so clear, are called pyrobitumens. A third division may be made to include the kerogen or oil shales; and a fourth, the various coals.

Natural Gas.—Natural gas is found in some quantity in all of the oil pools of the world. It is composed largely of the compound methane. Methane is also produced by the decomposition of organic matter in swamps and marshes. In this case it is known as marsh gas. Wells drilled into glacial drift in Iowa and Minnesota have yielded considerable quantities of a methane gas. This appears to have been formed by the decomposition of buried vegetable matter. "Fire damp," the cause of numerous explosions in coal mines, is composed largely of methane. It is generally considered as having been formed by chemical changes in the coal. The true natural gas is not limited to oil producing districts or pools but is frequently found alone in large quantities. The Monroe gas district of northern Louisiana, the Fort Smith-Poteau district of western Arkansas, and the gas belt of central Pennsylvania are areas of major importance which do not yield petroleum in commercial quantities.

The composition of natural gas varies in different sections and in different producing horizons in the same pool. Hydrocarbons form the only important combustible substances present. They cannot be said to be the only ones present as some gases show a small content of carbon monoxide and others contain elemental hydrogen. In addition to methane, ethane is a common constituent of natural gas. Other volatile members of the paraffin series such as propane, butane, hexane, and heptane are of minor importance volumetrically but of great interest commercially. They are of high luminosity.

Gases containing percentages of pentane, hexane, and heptane sufficient to make their separation commercially possible are the basis of the large casinghead or natural gas gasoline industry. Gases in which the percentage of extractable constituents of this type is equal to more than one gallon per thousand cubic feet of gas are called wet gases. Those in which the amount is under that, but is still sufficient to permit profitable treatment, are called lean or semi-dry gases. Those in which the content is so low that no effort is made to extract gasoline from them are called dry gases. Generally speaking, gases produced in pools which also yield oil are of the first two types. Areas yielding gas alone are frequently producers of the dry type. Many are worked in which the content of gasoline is only .1 to .3 of a gallon to the thousand feet because of the large volume of the gas available.

The analyses of natural gases seldom show the percentages of indi-

TABLE 18.—ANALYSES OF TYPICAL NATURAL GASES.*

Source	CH_4	Other Hydrocarbons	CO	CO_2	H_2	N_2	H_2S	O_2
Indiana and Ohio—average of 7 analyses	93.36%	.28%	.53%	.25%	1.76%	3.28%	.18%	.29%
Kansas, Augusta	76.48	13.04	—	.21	—	10.26	—	0
Kansas, Eldorado—1200-foot hori zon	62.68	11.82	—	.10	—	25.26	—	.14
Kansas, Eldorado—1400-foot horizon	31.36	12.78	—	.12	—	55.64	—	.10
California, Fullerton	86.7	9.5	—	1.7	—	2.1	—	0
Louisiana, Caddo	96.5	0	—	1.4	—	2.1	—	0
Pennsylvania, Oil City	67.6	31.3	—	0	—	1.1	—	0
Kentucky, Glasgow	23.6	69.7	—	2.5	—	1.3	2.9	0
Texas, Petrolia	51.3	10.4	—	.1	—	38.2	—	0
Ohio, Thurston	91.2	1.1	.8	.2	3.7	2.7	—	.3
Arkansas, Fort Smith	96.12	.02	.08	.93	.01	2.71	—	.13
California, West Los Angeles	91.	2.7	—	1.	—	5.2	—	.01
West Virginia, Morgantown	88.1	8.02	—	.24	—	3.6	—	0
Oklahoma, Meyers	76.6	2.25	—	.25	—	20.78	—	.12
Oklahoma, Morrison	57.89	16.89	—	.4	—	24.97	—	0

* Analyses from the U. S. Bureau of Mines and the U. S. Geological Survey.

vidual hydrocarbons other than methane. It is probable that some olefines are present in most gases.

The most important of the non-burning constituents present in natural gas is nitrogen. Contained in the nitrogen percentage is a subordinate, but important amount of helium and still smaller amounts of other inert gases, such as argon and neon. Gas produced in Petrolia, Texas, contains about 1% of helium. Substantial percentages have also been reported in the gases of other North Texas, Kansas, and Ohio pools. A national helium reserve has been established in Utah. The nitrogen percentage varies within a wide range, being less than 1% in some cases and greater than 50% in others. In addition to nitrogen, some gases contain appreciable quantities of oxygen and carbon dioxide. The totals are usually less than 1%. Occasionally hydrogen sulphide is found in sufficient quantity to give the gas a distinctly offensive odor.

Natural Asphalt.—At the present time the asphalt on the market is more commonly an artificial refinery product than a natural asphalt. It is produced in the refinery by distilling off all of the volatile fractions of a heavy or asphaltic base oil, such as might be produced in Mexico, California, Borneo, and Trinidad. If the residue produced is not sufficiently hard for the purpose for which it is intended, it is customary to blow air through it while it is still liquid and at high temperature. The oxygen unites with the hydrocarbons to produce an oxygenated product, whose viscosity is much greater than the untreated type while still liquid, and which forms a much harder and more durable asphalt. The same result may be secured by the introduction of sulphur.

Natural asphalt is found as a seepage deposit, in some cases occupying only a few square feet and in others extending over a number of acres. The best known deposits are those of the Trinidad asphalt lake in southwestern Trinidad and the Bermudez lake in eastern Venezuela. While natural asphalt is defined as a bituminous solid with little or no mineral matter present to contrast it with bituminous or tar sands and limestones in which mineral matter constitutes the larger part of the substance, such a definition must be used in a comparative sense only. The asphalt of Trinidad and Venezuela contains a variable amount of dissolved or suspended matter, such as sand, clay and soil. In addition it contains organic matter other than bituminous matter, such as leaves, twigs, and branches, which have been carried upon the asphalt surface and become imprisoned in the viscous material. Most analyses of natural asphalt include such matter in part with the mineral impurities and in part with the bituminous matter. The analyses of several typical asphalts are as follows:

TABLE 19.—ANALYSES OF TYPICAL ASPHALTS.*

Source	Bitumen	Mineral Matter	Gravity	Melting Point
Trinidad	56. %	36.8%	1.400	190° F.
Bermudez	94.	2.	1.085	180
Cuba	75.1	21.4	1.305	240

* After Cross, R.: Handbook of Petroleum, Asphalt and Natural Gas, p. 474, 1924.

The bituminous matter is largely soluble in carbon bisulphide. Analyses of this bituminous matter show it to be composed mainly of carbon and hydrogen as are petroleum oils. In addition a high percentage of sulphur seems to be common. Clarke[1] reports the finding of from 3.28% to 9.76% of sulphur in the analyses of eighteen hard asphalts. While oxygen is undoubtedly present in most natural asphalts, it is usually a minor constituent. In this the natural asphalt differs materially from the air-blown product of the oil refinery. Nitrogen is a subordinate element in natural, ordinary refinery residuum, and air-blown asphalts.

TABLE 20.—COMPARISON OF BITUMINOUS MATTER IN ASPHALTS.*

Source	Carbon	Hydrogen	Sulphur	Nitrogen	Oxygen
Trinidad natural	62.60%	10.60%	6.50%	.50%	———
Kansas refinery residuum	85.51	11.88	0.71	.32	0.63%
Kansas refinery air blown	84.37	10.39	0.42	.21	4.61

* After Cross, R.: Handbook of Petroleum, Asphalt and Natural Gas, p. 219, 1924.

Soft Asphalts.—The term asphalt is best restricted to the types produced in Trinidad and Venezuela. The soft varieties are closely related to them but appear to be of somewhat different chemical composition. The sulphur content in soft asphalts ranges from less than 1% to slightly under 3%. It is probable that the hydrocarbons in the two types differ somewhat. Those in malthas and other soft asphalts are of lower average viscosity and melting point than those in the harder types. Deposits of soft asphalts are not so striking in size and not so important commercially as those of the ordinary hard type. However, deposits of maltha, mineral tar, brea, chapopote, or similar substances are common in all oil fields of Tertiary and Cretaceous age in which heavy oils are produced. They are important indicators of the presence of oil.

---

[1] Clarke, F. W.: U. S. G. S. Bull. 770, p. 739, 1924.

Asphaltites.—The primary distinction between asphalts and asphaltites is that the latter are found in vein deposits below the surface, while the former are found at, or immediately below, the surface in association with seepages. Asphaltites are generally harder than asphalts. They are more difficult to fuse. However, like the asphalts, they are largely soluble in carbon bisulphide. Distinctions between individual substances in the group are not clearly defined. In fact, the differences between the group as a whole and the pyrobitumens are not well understood. Some authorities define asphaltites as hydrocarbons that are substantially free from oxygenated bodies and crystallizable paraffins. Such a definition would include gilsonite or uintaite, and manjak or glanze pitch, but exclude grahamite, as these substances are defined by some writers. Gilsonite, which has many of the properties of the others, is considered by some to contain as much as 6% of oxygen. Because of this, it would appear advisable to broaden the definition so as to include all vein hydrocarbons that are soluble in carbon bisulphide except those of the ozokerite type, which contain large amounts of crystalline paraffin wax. Thus all substances of similar physical properties would be included regardless of the presence or absence of oxygen.

It would appear that grahamite is generally less easily fused than the other substances in the group. Some authorities try to differentiate between the several asphaltites according to the content of mineral matter present. Others base their distinctions upon the content of petrolenes, compounds which are soluble in both petroleum ether and carbon bisulphide, in contrast to those which are soluble only in carbon bisulphide. Most industries using such materials purchase them on the "use and see the effect" basis and specify the product of a certain locality after they have found it to be satisfactory. Definite distinctions on a scientific basis are not possible at this time and any that are based on common usage in different sections would only lead to greater confusion.

Mineral Waxes.—Mineral waxes are not as common as the asphalts and asphaltites. The only natural mineral wax of economic interest is ozokerite. This is found in Galicia, India, Utah, and the

Caucasus Mountains of Russia. Of these, the only deposits that are worked on a large scale are those of Galicia. Refined ozokerite or ceresin may be defined as a pure paraffin solid, composed essentially of high melting point compounds of the paraffin series, from which the asphaltic and unsaturated hydrocarbons originally present in the ozokerite have been removed by chemical treatment. It is white in color and resembles ordinary refinery paraffin wax in physical appearance but differs in having a much higher melting point. In some places deposits of ozokerite approaching ceresin in composition have been found, but such deposits are rare and their size too small to be of economic interest.

The distinction between ozokerite and asphaltites lies in the large percentage of mineral waxes in the former and the relatively low percentage of asphaltic matter. Its color varies from a yellow to a deep brownish black, depending upon the percentage of asphaltic matter contained. It is soft, unctuous to the touch, easily fused, and distinctly soluble in all petroleum solvents. Most of the deposits are vein-like in form, but some ozokerite is found and recovered from the pore spaces and openings in the rocks and soils associated with the veins.

Closely allied to ozokerite are the soft waxes which separate from paraffin base and mixed base oils having a large content of paraffin wax. Some of this wax separates out in wells and tends to clog the working barrels and tubing. Well wax is yellowish brown in color like some ozokerites but differs in being very soft and having a lower melting point. This is apparently due to the predominance of low melting point solids and even to the inclusion of some true liquids.

Pyrobitumens.—As with the asphaltites, definite distinctions between pyrobitumens are not possible. In fact, only after a long and bitterly contested law suit was it legally established in 1851 that albertite or Albert coal, a vein pyrobitumen found in Albert County, New Brunswick, Canada, was not a true coal. Albertite is a brilliant jet black substance that is slightly soluble in carbon bisulphide. It differs only slightly from wurtzilite. The latter is also called elaterite. Another variety, impsonite, is more fusible than albertite but is subject to decrepitation on heating. The pitch coal of Coos Bay, Oregon, is considered as belonging to this family. The analyses of pyrobitumens show somewhat less hydrogen to the unit of carbon than do the asphaltites. Oxygen is apparently present in all pyribitumens, and nitrogen is mentioned in some analyses.

Bituminous Rocks.—With the exception of ozokerite bearing rocks and soils, all of the substances discussed have been composed mainly of the bitumens themselves. The occurrence of dirt saturated with asphalt or paraffin has been reported in many fields. The connection of such deposits with the escape of the more volatile compounds or the alteration of others by surface agencies is usually sufficiently clear to indicate that they are residual products from oil seepages. The bituminous matter constitutes but a small percentage of the dirt or soil in most cases.

In addition to such surface deposits, there are widely scattered deposits of rock character containing variable percentages of solid bituminous matter. The origin of these is not always apparent. Bituminous or asphaltic sandstones have been mined and quarried on a small scale for many years in Texas, California, and Kentucky. Bituminous sandstones are also known in Utah and Missouri and bituminous limestones occur in Oklahoma, Texas, Utah, and Missouri. Rocks of similar nature are utilized in France, Germany, Italy, Switzerland, and other countries of the Old World as paving materials.

Probably the best known bituminous rock deposit is the Athabasca tar sand found outcropping along the Athabasca River in Alberta, Canada. This tar sand differs from most of the bituminous rocks in that its bituminous matter is more of the nature of a very viscous liquid than of a true solid.

TABLE 21.—ANALYSES OF ASPHALTIC ROCKS.*

Source	Type	% Bitumen
Sicily, Ragusa	Limestone	9.9
France, Seyssel	Limestone	5.9
France, Mons	Limestone	8.9
Missouri, Cass Co.	Limestone	6.9
Oklahoma, Buckhorn	Limestone	5.9
Kentucky, Breckenridge Co.	Sandstone	9.2
Oklahoma, Buckhorn	Sandstone	9.2
Missouri, Higginsville	Sandstone	7.9

* After Cross, R.: Handbook of Petroleum, Asphalt and Natural Gas, p. 475, 1924.

Kerogen or Oil Shale.—The term kerogen shale, while subject to some misuse, does not convey the erroneous impression that liquid petroleum is present in the shale to the same extent that the name oil shale does. Kerogen may be defined as a carbonaceous substance present in some shales which, on being heated, produces a crude oil having much the same character as petroleum. Under the microscope kerogen appears to consist of minute globules or irregular laminae of yellow to dark brown or nearly black matter. The percentage of this material present bears a very definite relationship to the amount of oil that can be extracted from the shale. In true kerogen shales the percentage of kerogen present is always less than the amount of ash or true mineral matter.

The ash percentage in one of the shales from the Green River section of Wyoming is placed as low as 51.8%. This is exceptional; most of the richer shales in the same area contain more than 60% of ash. In the shales of Kentucky, Indiana, and Scotland, the ash is usually equal to 70% or more. The analyses of the ash indicate a composition similar to that of ordinary shales and clays: silicates of aluminum and iron, variable percentages of quartz, and compounds of calcium and magnesium. There is no evidence of abnormal composition except in the shales of the Phosphoria formation in Montana. Here the ash contains as much as 10% of phosphorus pentoxide combined in the form of a phosphate.

TABLE 22.—ULTIMATE ANALYSES OF KEROGEN SHALES.

Source	Analyses on Ash-free Basis					Ash %	Authority
	Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen (by Difference)		
Scotland, Broxburn	19.51%	2.48%	0.69%	1.36%	3.31%	72.65%	McKee *
Scotland, Pumpherston	24.88	3.67	0.68	0.80	8.07	61.90	McKee
Australia, Commonwealth (really a torbanite)	63.58	7.81	0.81	0.43	4.41	22.96	McKee
Scotland, average	25.27	3.67	1.14	0.49	5.65	63.78	Mills †
Utah, Soldiers Summit	13.51	1.70	0.28	0.39	18.00	66.12	Davis, B. of M.‡
Nevada, Elko	37.15	5.13	0.39	1.08	10.04	46.21	Davis, B. of M.
Colorado	22.58	2.72	0.55	0.55	10.67	62.93	Davis, B. of M.

* McKee, J.: Shale Oil, p. 77.

† Mills, E. J.: Destructive Distillation, p. 50.

‡ Davis, I. D.: U. S. G. S. Bull. 729, p. 16.

Except for the moisture content, the rest of the shale is kerogen. The analyses given indicate that this is equal to about 30% of the total weight in the Scotch shales and somewhat more in some of the Green River shales. This is misleading as the analyses given are those of shales that have been exploited commercially or are considered to be of potential economic importance. While not of direct commercial interest as a source of oil, the shale containing as little as 1% of kerogen should still be classed in the same group. In discussions of the relationships between petroleum and kerogen shales, the lean, commercially useless shales are of as great importance as the richer types. As already inferred, kerogen is not oil but the source of oil. The best proof of this lies in the inability of petroleum solvent, in which ordinary petroleum oils are entirely soluble, to dissolve more than a small portion of the kerogen content of ordinary shales. This is indicated in Table 23.

Table 23.—The Solubility of Kerogen.*

	Kentucky	Soldier Mt., Utah	DeBeque, Colo.	Green River, Wyoming
Oil yield, %	7.28	16.64	13.64	22.67
Gallons per ton	18.22	44.60	35.75	58.65
Extraction with solvents.				
Carbon tetrachloride				
% of shale soluble	0.037	0.74	2.04	1.195
% of distillation yield soluble	0.51	4.45	15.42	5.27
Carbon bisulphide				
% of shale soluble	0.015	0.76	1.85	1.27
% of distillation yield soluble	1.44	4.57	13.97	5.58
Acetone				
% of shale soluble	——	0.53	1.33	1.22
% of distillation yield soluble	——	3.16	10.04	5.35
Ether				
% of shale soluble	——	0.745	——	——
% of distillation yield soluble	——	4.48	——	——
Benzol				
% of shale soluble	0.06	0.91	2.23	1.37
% of distillation yield soluble	0.82	5.47	16.84	6.02
Chloroform				
% of shale soluble	0.14	1.5	2.41	1.75
% of distillation yield soluble	1.99	6.32	18.22	7.72

* After Gavin, Martin J., and Aydelotte, John T.: Bureau of Mines Reports of Investigations, Serial No. 2313, Jan., 1922.

Nature of Kerogen.—There is considerable difference of opinion as to the exact character of kerogen. Some, notably Cunningham-Craig,[1] consider it to be an inspissated petroleum, somewhat altered and adsorbed by the shale particles. A more general view is that the kerogen is indigenous to the shale and is the product of alteration of organic matter. Regardless of the theory supported, it is certain that the products of the retorting of shales are not the products of ordinary distillation, as the term might be used in reference to the boiling of water, gasoline, or kerosene, but the products resulting from the "destructive distillation" of the kerogen. The process may be considered as analogous to the coking of coals or even to the cracking of heavy non-volatile oils in the high pressure and high temperature cracking still of the petroleum refinery. Within certain limits the nature of the products from any given shale may be regulated by the retort man through the introduction of steam and the variation of temperatures and pressures.

With the development of the oil shale industry on a large scale the accumulation of proximate and ultimate analyses of oil shales will make it possible to compare their qualities with a fair degree of certainty. At present the number of such analyses available is limited; and those available were made under different conditions. Thus the percentage of fixed carbon left in the shale may vary within wide limits with different methods of retorting. Similarly the nitrogen, oxygen and sulphur may be retained in combination with the hydrogen and carbon or form separate compounds, such as carbon dioxide, ammonia, or hydrogen sulphide, by uniting with either of them alone. The nature of the hydrocarbons produced is subject to variation with different conditions just as the amount of the yield varies.

In comparing shale oils with ordinary petroleum oils, the possibilities of materially changing the character and amount of the oil produced from the individual shale must be kept clearly in mind. The gases produced in the shale retort contain large amounts of free hydrogen as well as methane and other compounds which might, by changing the conditions of retorting, be utilized in the production of saturated compounds instead of unsaturated and therefore less desirable ones. If this were accomplished, the similarity between shale oils and petroleum oils would be much more marked.

---

[1] Cunningham-Craig, E. H.: Origin of Oil Shale, Royal Soc. Edinburgh Proc., Vol. 36, pp. 44–86, 1916.

TABLE 24.—COMPARISON OF CHARACTERISTICS OF TYPICAL SHALE OILS.*

Source	Gravity		Gasoline Fraction †	Tops ‡	Unsaturated % of Tops	Total Distilled §	Carbon Residue of Residuum
	Spg.	Baume					
Colorado, Grand Valley (a)	.891	27.1	27.4%	53.2%	40.7%	81.2%	9.4%
Colorado, Grand Valley (b)	.922	21.8	23.3	42.2	46.3	81.3	13.5
Utah, Soldier Summit (a)	.908	24.2	16.4	34.2	40.5	76.8	9.
Utah, Soldier Summit (b)	.890	27.3	19.	38.5	39.6	85.5	6.4
Indiana (composite)	.940	18.9	26.1	47.5	37.7	81.1	22.
Scotland	.864	32.	16.63	37.10	32.	66.21	——
For comparison Pennsylvania Crude Petroleum	.812	42.4	31.93	52.76	4.1	80.39	——

* Adapted from Gavin, M. J.: U. S. Bureau of Mines, Bull. 210, 1922.

† Gasoline fraction equals percentage distilled to 200° C.

‡ Tops fraction equals total distilled to 275° C.

§ Total distilled equals amount distilled under atmospheric pressure plus that distilled up to 300° C. under 40 mm. of pressure.

Coals.—While coal is not found in all areas in which oil is produced, there are a sufficient number of areas producing both to bring up questions of the identity in origin or at least of the possibilities of similarity in origin. In speaking of coals, it is usual to mention only the normal types: lignites, bituminous coals, and anthracites, and their various subranks. Normal coals are now generally considered to be the products of the progressive alteration of some form of peat laid down in swamps in previous geological periods. This view is substantiated by the finding of plant and tree remains in coal deposits and the close relationship between the lower ranks of coal and peat. The lignites closely resemble peat in being high in moisture and volatile matter and low in fixed carbon. In the bituminous ranks the amount of moisture is low, but considerable volatile matter remains. In anthracites the volatile matter is reduced to a very small percentage of the total and the bulk of the coal is composed of fixed carbon.

As the terms volatile matter and fixed carbon have empirical meanings, their definition is necessary. Analyses of coals are made in two ways –the proximate and the ultimate. The latter gives the elemental composition of the coal, but is long and tedious to make, and does not directly indicate the value of the coal for burning purposes. The proximate analyses do not give the percentage of any individual element, but do indicate the manner in which the coal will act in a furnace, and indirectly indicate the general manner in which the elements present in the compounds of the coal are linked together.

The moisture content, which is of no value from the heat standpoint, is defined as the portion of the coal that is driven off when coal is heated for a short period at 105° C. or slightly above the boiling point of water. The volatile matter is considered as equal to the portion of the coal that is driven off when the coal is heated in a closed retort without access to air over a Bunsen flame. The remainder consists of the so-called fixed carbon and the ash. The fixed carbon percentage is arrived at by burning off the combustible matter in the sample remaining after the volatile matter has been driven off, and subtracting the ash, which does not burn.

Part of the volatile matter is not combustible and the fixed carbon is known to contain small amounts of hydrogen and oxygen as well as carbon. It may also contain some sulphur. Both ultimate and proximate analyses are important in comparisons of coals and oils and their intermediate substances.

Like kerogen shales, coals contain small proportions of nitrogen and sulphur. The percentage of mineral matter in coals is variable but in commercially exploited coal beds in the United States averages less than 10%. This is very small in comparison with the ash content of kerogen shales. However, it should be noted that the ash content of coals worked in other parts of the world runs as high as 30%. Other beds, which may be variously referred to as black slates, bone coals, or carbonaceous shales, contain still higher percentages of mineral matter; and because of this, are not of economic value.

The outstanding difference between coals and kerogen shales lies not in the relative percentages of ash that they contain but in the differences in the nature of their combustible matter. Ultimate analyses of kerogen show the presence of only a small amount of oxygen in comparison with the percentage of carbon and hydrogen. The analyses of the several ranks of coal show oxygen to be almost as important a constituent of coal as carbon in the lower ranks. Its amount decreases in the higher ranks but is always materially higher than the percentage of hydrogen.

Table 25.—Ultimate Analyses of Representative Normal Coals.*

Rank	Sulphur	Hydrogen	Carbon	Nitrogen	Oxygen
Wood	——	6.25%	49.50%	1.10%	43.15%
Peat	1.48%	4.69	48.57	2.54	28.89
Lignite	1.89	4.74	72.79	0.98	19.60
Sub-bituminous	.50	4.74	76.28	1.47	17.01
Bituminous	1.06	5.39	87.	1.37	5.18
Semi-bituminous	2.52	4.37	89.07	1.40	2.64
Semi-anthracite	.74	3.76	92.15	1.18	2.17
Anthracite	1.00	1.77	94.13	0.71	2.13

* After Moore, E. S.: Coal, p. 96, 1922. Analyses on the moisture and ash free basis.

The high percentage of oxygen of the normal coals of lower rank, such as the lignites, is found to be accompanied by woody structure in many cases. This immediately brings up questions concerning the chemical nature of woods. In general, woods are considered to be composed of about equal parts of cellulose and lignocellulose. The percentage composition of these two substances is as follows:

Cellulose		Lignocellulose
44.44%	Carbon	47.07%
6.18	Hydrogen	5.89
49.38	Oxygen	47.05

However, the average analyses of woods show a somewhat lower content of oxygen and larger amounts of carbon and hydrogen. Such differences are found in many instances to correspond with differences in the content of resins and related substances present. These are composed essentially of carbon and hydrogen and contain little or no oxygen. It is evident that from the analyses of the normal coals given that these, while present, do not form an important part of such coals.

Cannel Coals.—On the other hand, the low percentage of oxygen and large amount of hydrogen contained in the several types of cannel coals is definite proof that these are not normal woody coals but coals of entirely different origin. Cannel coals are of various ranks, the divisions being similar to those of the normal coals; but such divisions are not well established because of the limited extent of the deposits in which they are found. The analyses of the higher ranks are much like those of the normal coals; but those of the lower or true cannel types are quite different.

The differences in chemical character may be due to differences in the nature of the source materials from which they were formed. The suggestion that they are the product of the alteration of resinous or other matter largely composed of hydrogen and carbon, rather than cellulosic or carbohydrate matter composed of carbon, oxygen, and hydrogen, appears to be a logical one. It is also possible that they have been subjected to a different type of alteration than that to which the normal coals have been. In either case the close relationship between cannel coals and the organic matter of the kerogen shale indicated by the chemical analyses demands careful consideration of their origin. The kinship of this group of coals and the petroleum family as a whole may be inferred from the fact that the inception of the Scotch-English shale oil industry came through the recovery of coal oil or kerosene from a "torbanite cannel" in Linlithgowshire in 1851. In the United States, Kentucky cannel coals were sources of kerosene before the drilling of the first well in Pennsylvania.

Table 26.—Analyses of Cannel Coals.*

Source	Volatile Matter	Fixed Carbon	Sulphur	Hydrogen	Carbon	Nitrogen	Oxygen
Kentucky, Flambeau, Johnson Co.	55.5%	44.4%	1.38%	7.13%	82.59%	1.33%	7.57%
Utah, Glendale, Kane Co., subcannel	67.6	32.3	2.32	7.73	74.75	1.52	15.90
England, Wigam	——	——	1.4	6.08	79.2	1.1	7.2
Kentucky, Breckenridge	——	——	——	7.8	82.3	2.7	7.0
Scotland (torbanite or boghead)	——	——	——	11.2	80.4	.8	6.7

* After Ashley, G. H.: U. S. G. S. Bull. 659, pp. 19–20, 1917.

Cannel coals differ from the normal types in physical as well as chemical properties. They lack the "xyloid" or woody structure so common in the normal coals. They are dull instead of lustrous, and break with a distinctly conchoidal or shell-like fracture instead of in blocks. Microscopic examination further sustains the megascopic examination in bringing out differences between the two types.

Such examinations, however, tend also to bring out differences between cannels themselves and lead to further divisions of these connecting links between the coal and oil families. Ordinary cannels are considered as having been formed mainly from the spores, pollens, and resinous bodies of land plants. This explanation does not wholly account for the unusual properties of the varieties known as torbanites, kerosene shales or coals, boghead coals or cannels, and brown coals. The term "algal" has also been used by some to indicate their belief in the "algal" origin of these coals as against the "spore" origin of the more common type of cannels. The "algal" type is even more closely related chemically to kerogen shale than the spore type.

A SELECTED BIBLIOGRAPHY ON NATURAL GAS AND BITUMENS RELATED TO PETROLEUM.

1. ABRAHAM, HERBERT, Asphalts and Allied Substances.
2. ALDERSON, V. C., The Oil Shale Industry.
3. CROSS, ROY, Handbook of Petroleum, Asphalt and Natural Gas.
4. DANBY, ARTHUR, Natural Rock Asphalts and Bitumens.
5. GAVIN, M. J., Oil Shale, U. S. Bureau of Mines, Bulletin 210.
6. GREGAERIS, R., Mineral Waxes.
7. MCKEE, JAMES, Oil Shale.
8. MOORE, E. S., Coal.
9. ROGERS, G. S., Helium Bearing Natural Gas, U. S. Geological Survey, Professional Paper 121.
10. SPIELMANN, P. E., Bituminous Substances.
11. WESTCOTT, H. P., Handbook of Natural Gas.
12. WINCHESTER, DEAN E., Oil Shale of the Rocky Mountain Region, U. S. Geological Survey, Bulletin 729.

Most of the references listed on page 13 also discuss natural gas and bituminous substances at some length.

CHAPTER IV.

THE ORIGIN OF PETROLEUM AND RELATED SUBSTANCES.

There are two ways of discussing the origin of petroleum and its related substances. First, one may consider all of the possible theories of their origin without regard to their application to the actual occurrence of petroleum in nature. Secondly, one may limit discussion to those theories which postulate conditions that can be duplicated, or at least approximated, in nature. The weakness of the laboratory theory usually lies in its inability to adjust itself to the conditions of the larger laboratory, the earth itself. Viewed in another way, discussions may be considered as either qualitative or quantitative. While hydrocarbons have been proved to exist in meteorites, it does not necessarily follow that meteorites can be considered as the main source, or as one of a group of sources, of the oils and related materials found throughout the globe. Similarly while it is admitted by all that methane is produced in large amounts in the decomposition of coals, there are few who believe that the methane associated with oil is the product of such decomposition.

In discussing the several theories, it is necessary that we keep in mind two points. Let us first inquire whether the proposed or suggested explanation is a logical explanation of the formation of some oil. If the answer is in the affirmative, we may ask ourselves if the theory is a logical explanation of the presence of petroleum and related substances in one or more of the areas in which such substances have been concentrated by nature.

It is natural that in a discussion occupying as brief a space as can be allotted to it here that the major portion of the discussion should be limited to those theories which pass the first test. Such theories fall into two groups: the first, including all theories postulating an inorganic origin for oil; the second, those suggesting organic life as the original source of these substances. Within the two major groups are a number of subtheories. These, especially in the organic group, show many points of similarity. They have been developed in large measure by individuals working in different areas with different types of data. It is not necessary or desirable that the geologist attempt to apply the explanation that he finds satisfactory in one area to all areas. However, the line of demarcation between the two major theories is clearly drawn and abrupt. Here the student is called upon to make a definite decision in support of one and against the other. While inorganic and organic explanations may be combined in theory, they are impossible of combination in practice.

Inorganic Theories.[1]—Chemists have long known that hydrocarbons can be prepared in the laboratory from inorganic as well as organic substances. In general such reactions yield gaseous hydrocarbons such as methane, ethane, and acetylene. Others, such as the unsaturated members of the olefine and benzene families, have been produced directly or in secondary reactions. There have been two main lines of research in this field; namely, the production of hydrocarbons by reactions of acids upon metals containing carbon, and the development of hydrocarbons through reactions between metallic carbides and water.

The elaborate work of S. Cloëz[2] following earlier work by H. Hahn,[3] and F. W. Williams[4] definitely demonstrated the possibility of producing hydrocarbons by treating cast iron, spiegeleisen, or ferromanganese with hydrocloric acid and sulphuric acid. Cloëz was able to separate some hydrocarbons from the hydrogen gas generated by the reaction by direct condensation, and others by adsorption in bromine. In addition to unsaturated hydrocarbons, he was able to identify seven liquid paraffins, all of which were common in petroleum.

The Carbide Theory.—The carbide investigations began with the proposal of the carbide theory by D. Mendeléef[5] in 1877. The reactions between carbides and water were not studied to any great extent before the development of the electric furnace by Moissan. Of the carbide reactions, the best known and also one of commercial importance, is the reaction between calcium carbide and water to produce acetylene. This substance is also obtained, according to H. Moissan,[6] when lithium, sodium, strontium, and barium carbides are treated

[1] An excellent summary of the more important experiments and of the literature dealing with the inorganic and organic theories of the origin of petroleum is given by F. W. Clarke in U. S. G. S. Bull. 770, pp. 731–755, 1924.

[2] Compt. Rend., Vol. 78, p. 1565, 1874; Vol. 85, p. 1003, 1877; Vol. 86, p. 1248, 1878.

[3] Liebig's Annalen, Vol. 129, p. 57, 1864.

[4] Am. Jour. Sci., 3d Series, Vol. 6, p. 363, 1873.

[5] Jour. Chem. Soc., Vol. 32, p. 283; Ber. Deutsch. Chem. Gesell., Vol. 10, p. 229, 1877.

[6] Compt. Rend., Vol. 122, p. 1462, 1896.

with water. Carbides of aluminum and glucinum yield principally methane, and the carbide of manganese produces methane and hydrogen. The same authority also states that carbides of yttrium, lanthanum, cerium, thorium, and uranium yield mixtures of acetylene, methane, ethylene, and hydrogen, the last three carbides also producing liquid and solid hydrocarbons.

While other hydrocarbons are produced in the carbide reactions, the most important volumetrically is acetylene, a compound that is a very minor constituent of petroleum and natural gas if present at all. However, it has been demonstrated by M. Bertholot[1] that acetylene (C_2H_2) polymerizes to form benzene (C_6H_6) at the softening temperature of glass and that benzene is subject to further change and alteration to other hydrocarbons. More recently P. Sabatier and J. B. Senderens[2] have shown that, if acetylene and hydrogen are brought in contact with finely divided nickel, a mixture of paraffins similar to those present in Pennsylvania petroleum is produced.

Two other investigators, E. Briner and A. Wrocynski,[3] found that polymerization is greatly aided by pressure.

Apparently the possibility of direct production of acetylene by the passage of hydrogen between the carbon terminals of an electric arc was known as early as 1863, but little interest was taken in that reaction. According to W. A. Bone and D. S. Jerdan[4] methane and ethane are formed in the same reaction and at lower temperatures. They state that methane is the only product formed at 1200°.

During the present century most of the interest has been centered in the development of organic theories, but R. Salvadori[5] has shown that hydrocarbons can be produced by heating together calcium carbide and ammonium chloride. The latter is a frequent constituent of volcanic emanations. Similarly G. Steiger[6] has produced hydrocarbons by the direct action of ammonium chloride upon native iron. The native iron used was undoubtedly like the cast iron, spiegeleisen, and ferromanganese used in the experiments of Hahn, Williams, and Cloëz, a container of carbon in the form of iron carbides.

Application of Inorganic Theories.—Volumes might be written about the attempts to apply these experimentally proved reactions and countless others, which were experimentally unproved, to the origin of petroleum. One that differs from the rest in calling for no chemical reactions below the crust of the earth was proposed by N. V. Sokoloff.[1] The theory was based upon the assumption that all bitumens are of cosmic origin. They were considered to have entered the earth during the period of its consolidation and have gradually risen to the surface or crustal portions in the years since their original imprisonment. The theory is supported by the occasional finding of hydrocarbons in meteorites. There is no evidence to support it from the quantitative standpoint; and, as it is open to the same criticism as the more fully developed theories of Berthelot and Mendeléef, it need not be further considered.

---

[1] Annales chim. phys., 4th series, Vol. 12, p. 52, 1867.

[2] Compt. Rend., Vol. 134, p. 1185, 1903.

[3] Arch. Sci. Phys. Nat., 4th Ser., Vol. 32, p. 389, 1911.

[4] Jour. Chem. Soc., Vol. 71, p. 41, 1897; Vol. 79, p. 1042, 1901.

[5] Gazz. Chim. Ital., Vol. 32, p. 496, 1902.

[6] U. S. G. S. Bull. 770, p. 742, 1924.

Both the theories of Berthelot and Mendeléef rest primarily upon assumptions concerning the nature of the earth's core. Berthelot considered the core to consist largely of free alkaline metals. Mendeléef assumed the existence of metallic carbides, especially the carbide of iron. As the assumption in the latter case seemed to be more in keeping with the known high density of the earth, the earlier theory of Berthelot may be passed over with a brief summary.

Berthelot's Theory. According to Berthelot,[2] the alkaline metals would react with carbon dioxide to form carbides or acetylides and oxygen. At a later period, the oxygen having passed off, water coming in contact with the carbides would generate acetylene. The acetylene would then be subject to alteration into the numerous hydrocarbons of petroleum. The theory cannot be lightly dismissed as the reactions postulated can all be duplicated in the laboratory. The weakest link in the theory is the postulation of an alkaline core for the earth.

Mendeléef's Theory.—The carbide theory of Mendeléef[3] proposed in 1877 assumes the development of the hydrocarbons along the same lines as does the theory of Berthelot, but calls for the carbide instead of the metal core. Doubtless the use of iron carbide was suggested by the laboratory researches of Hahn, Williams, and Cloëz already referred to. The theory was partly accepted by Moissan, whose work with the electric furnace added materially to its plausibility: first, by indicating the possibility of the development of the hydrocarbons from carbides other than iron; and secondly, by showing the great affinity that metals have for carbon at high temperatures. Some of the theories of the origin of the earth in vogue during the latter part of the past century called for the existence of temperature conditions in the center of the globe greater than those of the electric furnace. Under such conditions the formation of carbides, nitrides, and other high temperature non-oxygen containing compounds within the core of a solidifying globe would be probable; and their preservation for indefinite periods of time, entirely possible.

---

[1] Bull. Soc. Imp. Nat. Moscow, new series, Vol. 3, p. 720, 1890.

[2] Annales Chim. phys., 4th series, Vol. 9, p. 481, 1866.

[3] Ber. Deutsch. Chem. Gesell., Vol. 10, p. 229, 1877; Jour. Chem. Soc., Vol. 32, p. 283.

Direct Evidence of Inorganic Origin.—There is, of course, no way of proving the presence or absence of a carbide core in which the carbides of the heavy metals, such as iron, would be of common occurrence. Calculations of the density of the earth tend to indicate the existence of a core composed largely of heavy metals, alloys, carbides, nitrides, and other compounds entirely different from the common oxygen containing compounds of the surface. The water essential to the reactions in which the hydrocarbons were produced may be considered as either original to the core or as having filtered through from the upper crustal portions. The downward movement of the water in the latter case and the upward movement of the hydrocarbons generated would be greatly restricted by the tendency of open pore spaces and cracks to disappear within a limited distance from the surface.

If we admit the possibility of such movement for the time being in order to consider the theory further, it would appear justifiable to infer that the most logical places for the accumulation of oil, according to the carbide or similar theories, are those in which volcanic activity or related phenomena, either present or past, indicate the existence of lines of crustal weakness or fracture.

Thus considerable weight was given by those supporting the carbide origin to the common occurrence of methane in volcanic emanations. Their views appeared to be further sustained by the identification of liquid hydrocarbons and solid paraffins in the basaltic lava near Mt. Etna by O. Silvestri.[1] A. Brun[2] made similar observations while studying the volcanoes of Java. These occurrences are not, however, clearly connected with productive oil areas. E. Coste[3] and others have cited the close geographical relationship between intrusive dikes and related igneous bodies and oil-containing strata in Mexico and other places as arguments in favor of the inorganic derivation.

---

[1] Gazz. Chim. Ital., Vol. 7, p. 1, 1877; Vol. 12, p. 9, 1882.

[2] Arch. Sci. phys. Nat., 4th ser., Vol. 27, p. 113, 1909.

[3] Trans. Am. Inst. Min. Eng., Vol. 35, p. 288, 1905.

Oil has been produced from rocks that are distinctly of igneous origin. The best examples of such occurrences are Thrall and Lockhart in Texas and several pools in Japan. A small number of wells yield oil from rocks, which are considered as of igneous character, near Havana in Cuba. The last example would be of no importance alone because of the insignificant yield of the wells. The oil obtained from the several Japanese pools comes partly from igneous rock reservoirs and partly from ordinary sands. The oil found at Lockhart and Thrall comes entirely from igneous material, although the surrounding rocks are sedimentary. This rock has been identified as a highly altered rock of serpentine-like composition, probably the alteration product of a basic tuff or flow breccia.

The conclusiveness of the evidence of Mexican occurrence is considerably minimized by the fact that the bulk of the oil is obtained in the sections of the field in which igneous phenomena are the least marked. In sections where such phenomena are most evident, the liquid petroleum is largely replaced by asphalts and asphaltites. E. De Golyer[1] points out that the adjacent limestones form a natural means of migration of oil to the centers of igneous activity.

Similarly the igneous reservoirs of Lockhart, Thrall, Cuba, and Japan, may be considered merely as porous containers into which the oil has made its way after its formation in other rocks. The serpentine in Cuba is in contact with Cretaceous, Triassic, and Jurassic marls, shales, sandstones, conglomerates, and limestones. The so-called serpentine of the two Texas pools forms sill-like bodies in the sediments of the Gulf Coastal plains. Sandstones produce oil from the same general horizon in nearby pools in which there is no evidence of igneous activity. The oil yielding tuffs of Japan are interbedded with sandstones and clays saturated with organic matter.

Indirect Evidence.—The lack of direct evidence of igneous phenomena in practically all of the world's major oil fields has made necessary the substitution of indirect evidence. The evidence of this kind may be divided into two types: evidence indicated by the nature of the oil or of the waters and gases associated with it, and evidence based upon differences in physical phenomena in the oil areas.

Considerable importance is attached by some to the association of oils in various fields with thermal or magmatic waters, such as those of the Island of Trinidad. While the magmatic origin of these waters is of common acceptance, there is no proof that the oil is of the same origin. It would appear more logical to consider that the only function of such waters and of the igneous phenomena which they indicate has been that of alteration and even destruction of the liquid hydrocarbons. Certainly the polymerization and sulphurization, which have evidently been major factors in changing liquid petroleum into the solid asphalt of Pitch Lake, must be considered as resulting from the reaction of solfataric waters (with their included hydrogen sulphide) upon hydrocarbons.

---

[1] Econ. Geol., Vol. 10, p. 650, 1915.

The high percentages of calcium and magnesium chlorides in many brines have led to questions concerning their origin. C. W. Washburne[1] considered that such waters have received calcium and magnesium chlorides as well as some sodium chloride as emanations from deep seated basic magmas. The possibility of the development of oil from deep seated sources is indicated. The evidence to support the formation of these brines in this manner is fragmentary and weak compared with the evidence against it.

The presence of nitrogen in natural gas and oil has been offered as evidence both for and against inorganic theories. Combined nitrogen is present in oils of all ages and in variable amounts. The element is an important constituent of volcanic gases and is common in many metal mines, whose deposits are of the type produced in igneous activity. Such nitrogen is almost always present as elemental, or uncombined, nitrogen rather than in the combined state. In oils it is commonly combined.

If this difference is disregarded, though it would appear to be of major importance from a chemical standpoint, it would be logical to expect that the nitrogen content of oils would be greatest in those closest to the magmatic source, if that were the source of the nitrogen. The greatest amounts of nitrogen would then be expected in oils found at the greatest depths and in the oldest formations. Instead, from the studies made by Mabery[2] it would appear that the average content of nitrogen in oils found in rocks of younger age is slightly greater than that of the older ones. The variations between oils of the same age is wide and apparently bears little or no relation to differences in depths.

It might be inferred that the slight decrease in the nitrogen content of oils formed at high temperatures is due to the gradual decomposition of the nitrogen compounds with the freeing of elemental nitrogen to form part of natural gases. The extremely large free nitrogen content of some of the late Paleozoic gases of Kansas, Texas, and Oklahoma, in comparison with the limited quantity of the element in the gases found in rocks of later ages in California and Louisiana, would lend support to this view. However, the low percentage of nitrogen normally present in the early Paleozoic gases of the fields east of the Mississippi indicates that no generalization can be made along this line.

---

[1] A. I. M. E. Trans., Vol. 48, pp. 687–693, 1914.

[2] Am. Chem. Soc. Jour., Vol. 41, No. 10, pp. 1690–1697, 1919.

On the other hand, it is not possible to postulate a strictly organic origin for all of the uncombined nitrogen present in natural gas. Even assuming marked differences in the nature of the source materials, the extreme variation in the nitrogen content in different gases closely related in depth, location, and geologic age can hardly be explained by differences in the organic source materials alone, or in the manner of their alteration. A double origin of the nitrogen content of some gases seems to be the only explanation of the occurrence of helium and other inert gases.

Such gases constitute as much as 1% of the total volume of the natural gas at Petrolia, Texas, and are found in substantial amounts in El Dorado, Kansas, and other places. The helium content may be considered either as of primordial or extremely deep seated origin, or the product of the disintegration of radioactive matter at a short distance below the formations in which the helium has accumulated.[1] There appears to be no regular ratio between the helium and the nitrogen contents of natural gases. A satisfactory explanation of the helium content will not necessarily be applicable to the nitrogen content. Similarly, the explanation of the elemental nitrogen in the natural gas is not necessarily the explanation of the combined nitrogen in the oil.

The importance of nickel as a catalyst has been mentioned. The existence of this element and of vanadium and other metallic elements in petroleum has been proved by chemical analyses. W. Ramsey[2] and others attach great importance to the presence of such elements as evidence favoring the inorganic origin of petroleum. The amount of these elements present is extremely small and their chemical nature

---

[1] For discussion on origin of helium see Rogers, G. S.: Helium-Bearing Natural Gas, U. S. G. S. Prof. Paper 121, 1921.

[2] Jour. Inst. of Pet. Tech., Vol. 10, pp. 87–91, 1924.

Table 27.—Ratio of Nitrogen to Helium in Some Natural Gases.*

Source	Nitrogen	Helium	Ratio of Nitrogen to Helium
Oklahoma, Morrison	25.0%	.22%	114
Oklahoma, Ponca City	40.1	.36	111
Oklahoma, Billings	42.5	.39	109
Oklahoma, Loco	16.2	.17	95
Kansas, Otto	57.8	1.04	55
Kansas, Dexter	82.7	1.84	45
Kansas, Augusta	88.0	2.00	44
Ohio, Vinton Co.	15.1	.43	35
Kansas, Sedan	55.7	1.94	29
Kansas, Fredonia	16.4	.62	26
Ohio, Vinton Co.	9.6	.40	24
Kansas, Elmdale	12.1	.56	22
Kansas, New Albany	9.8	.49	20

* U. S. G. S. Prof. Paper 121, p. 40, 1921.

is unknown. Before such evidence is introduced in support of inorganic theories of origin, it would appear necessary to prove that the metallic elements were not introduced after the oil reached the reservoir that the well taps. Because of the extremely small amounts that have been found, there is even the possibility that the oil has been contaminated after it reached the surface. Assuming that the metallic elements are original with the oil, there is, according to F. A. Thomson,[1] no reason to attach great importance to the presence of such elements. While nickel is not definitely known to exist in organic matter, iron, copper, zinc, manganese, vanadium, and other metals have been identified in living plant and animal life.

Of the physical evidence tending to show connection between oil fields and areas of magmatic activity, the most important is that offered by G. F. Becker.[2] He suggests that the existence of massive bodies of iron carbides, even though at considerable depths, should be indicated by magnetic irregularities. Magnetic deflections should be apparent in oil field areas. This he found to be the case in the Appalachian field. Similar irregularities were also found to exist in the Caucasus area of Russia and in the California fields. The suggestions of Becker were not accepted generally as W. A. Tarr,[3] among others, pointed out that irregularities in the lines of magnetic declination are not limited to oil fields. Thus while the existence of such irregularities may be admitted, their connection with oil formation is not proved.

---

[1] Min. & Met., Vol. 16, pp. 24–25, Jan., 1925.

[2] U. S. G. S. Bull. 401, 1909.

[3] Econ. Geology, Vol. 7, pp. 647–661, 1912.

Insufficiency of Inorganic Theories.—The carbide theory is perhaps the most logical of all of the theories of the inorganic origin of petroleum. It is difficult to accept, however, because it postulates the existence of conditions within the globe which are unproved, and because it offers no evidence showing direct or causal relations between igneous activity and the areas in which petroleum and related hydrocarbons are concentrated. That igneous activity has been of importance in the alteration of such hydrocarbons after their formation, and in determining the exact areas in which they were concentrated into commercially workable deposits, is indicated by conditions in Mexico and other areas. Inorganic reactions of some sort seem essential to the explanation of the existence of helium and possibly of at least a part of the nitrogen content of some gases. There is no evidence pointing to the derivation of the hydrocarbons from the same source as the helium. In fact, the striking lack of regularity in the occurrence of helium, and the wide variations in the nitrogen percentage in natural gases, lead to the opposite conclusion.

Organic Theories.—The organic origin of petroleum is now so generally admitted that greater interest is attached to differences in the nature and alteration of the source materials than is given to proof of the theory itself. Yet the thorough student will naturally inquire as to the ability of organic theories in general to meet the tests which the inorganic have been asked to meet before considering differences between individual subdivisions of the group.

While the work[1] of F. H. Storer, C. M. Warren, T. Lehman, W. C. Day, J. Marcusson, S. P. Stadler, and others might be cited, the work of C. Engler is generally considered as having contributed the most to the support of the organic theories from the qualitative, or laboratory, standpoint. In 1888 Engler[2] succeeded in producing a product closely resembling petroleum by the distillation of menhaden oil. This fish oil was produced under a pressure of ten atmospheres and at a temperature of between 320 and 400 degrees. From the oil produced he was able to isolate the paraffins, pentane, hexane, and heptane. In later studies of similar nature he isolated other paraffins, olefines, and benzene compounds, and even prepared an illuminating

[1] Clarke, F. W.: U. S. G. S. Bull. 770, p. 743, 1924.

[2] Ber. Deutsch. Chem. Gesell., Vol. 21, p. 1816, 1888.

oil practically identical with commercial kerosene. A little later the same investigator[1] produced hydrocarbons by the treatment of colza oil (oil derived from rapeseed), olive oil, butter, and beeswax; and S. P. Stadler[2] obtained similar compounds by distilling linseed oil.

The results of these investigations have been duplicated so many times in the chemical laboratory that there is no reason to doubt them. While the work of Engler and others must be considered of major importance in initiating the discussion of organic theories, it should be pointed out that L. Lesquereux[3] suggested as early as 1866 that the Devonian oils of the eastern part of the United States were derived from cellular marine plants. This hypothesis, and those suggested in the years following the laboratory investigations mentioned, were based almost entirely upon the abundance of plant and animal remains present in the sediments of the petroliferous formations. In fact, organic theories may be said to have been developed from quantitative or field evidence, rather than from the qualitative or laboratory studies.

This may be one explanation of the large number of sub-theories. In most cases these differ from one another only in minor details. Many are open to the criticism of incompleteness; that is, they fail to explain the origin of the substances most intimately associated with the oil. Others are so limited and restricted in application as to raise doubts regarding the accuracy of the observations upon which they have been based. Differences in a few major lines are of such importance that those of minor detail must be omitted from this discussion. Those that arose first and have been the subject of greatest controversy up to the present time are differences in the nature of the organic life forming the source materials from which the oils were derived. Secondly, we find that the manner and degree of alteration of the organic debris prior to its burial below later sediments are points of controversy. The duration and importance of the period that the oil source materials are believed by most geologists to spend in the form of kerogen or similar matter distributed through shales is a subject of discussion. Some doubt the existence of "unborn petroleum" in this form at all. Assuming kerogen to be a stage in the transformation of organic matter into petroleum, we are called upon to explain the mechanics of its alteration into petroleum and natural gas.

---

[1] Cong. Internat. du pétrole Paris, p. 20, 1900.

[2] Proc. Am. Philos. Soc., Vol. 36, p. 93, 1897.

[3] Bull. Soc. Sci. Nat. Neuchatel, Vol. 7, p. 234, 1866.

Differences in views concerning any of these points lead to different explanations of the nature of the oil and gas produced. A few believe that after the oils have been formed they are not subject to any further alteration while below the surface. Most geologists believe that this alteration of oils is of major importance, but not all of them agree on the nature and method of accomplishing the changes. Lastly, there is a wide divergence in opinion on the relationship between oils and the allied substances—asphalts, asphaltites, mineral waxes, and tar sands. While most observers admit the kinship of these with petroleum, a few question its existence and especially the idea that they were derived from oil.

Source Materials of Petroleum.—The primary division of theories dealing with the original source materials is into the plant and the animal types. Within these we find specific mention of the following:

A. ANIMAL SOURCES.

1. Fish.
2. Molluscs, etc.
3. Crustacea.
4. Foraminifera and related microscopic types.

B. PLANT SOURCES.

1. Higher forms of plant life.
2. Diatoms.
3. Algae, including seaweeds.

Animal Theories.—The original researches of Engler gave great impetus to the theories of animal origin of petroleum. Engler[1] concluded that petroleum was derived from animal remains that passed through a putrefactive process in which the nitrogen compounds were removed, the fats remaining in such form as to be amenable to alteration to petroleum under the influence of heat and pressure at a later period.

Many of the early investigators appear to have favored the view that oil was derived from the remains of fishes. The association of petroleum in Galicia with the Menilithic shales, in which there is an abundance of fish remains, was especially marked. While formerly these shales were considered as direct proof of the fish origin, this is now questioned. There are other shale beds containing the remains of lower forms of animal and plant life lying in much closer relationship to the oil yielding horizons than those containing the fish fossils. Theories such as those advanced by J. M. MacFarlane,[2] which consider fishes as the sole source of petroleum, are open to further question. While admitting the adequacy of fishes to supply the organic debris from which oils might be formed in recent periods, their importance in earlier periods of the world's history is questionable. The fact that fishes did not attain prominence until the Devonian period constitutes a serious drawback to their use in explaining the occurrence of oil in some rocks of Ordovician age.

---

[1] Ber. Deutsch. Chem. Gesell., Vol. 30, p. 2358, 1897.

[2] Fishes, The Source of Petroleum, 1923.

Considerably greater geographical and time range can be obtained by substituting the term "marine animal" for fish and thus including not only fishes but mollusca, crustacea, molluscoidea, and other somewhat lower forms which have been prominent from Cambrian time down to the present. Fossil remains of such life are found in some of the formations in practically every oil field of the globe. The shell remains of the hard parts of members of these families are of common occurrence in many fields, and in some they constitute the actual producing horizon.

There is no apparent reason why still lower and even microscopic forms of animal life, such as the foraminifera, cannot be considered as potential sources of oil. I. A. Stigand[1] points out that foraminiferal beds are prominent in the oil containing horizons of southern Russia, and that at Maikop they underlie the main oil sands. Similar examples might be cited in other areas.

Plant or Vegetable Sources.—The seaweed was considered by L. Lesquereux[2] as a potential source of oil as early as 1866. This theory was taken up by others, who found in the great masses of seaweed in the Sargasso Sea an ideal source of petroleum. The hypothesis suggested was that such material would sink to the bottom of the ocean and there decompose to form petroleum. Redwood[3] states that products closely resembling petroleum have been observed as resulting from the decomposition of seaweed in the salt marshes of Sardinia and along the coast of Sweden. The common occurrence of iodine in seaweed led W. L. Watts[4] to examine the waters associated with petroleum in the San Joaquin Valley of California for that element. He reported an unusually large content of iodine and inferred that seaweeds were the probable source of the oil. G. S. Rogers[5] agrees that iodine is present in some analyses, but the amounts that one finds are hardly sufficient to support the deduction of Watts.

---

[1] Outlines of the Occurrence and Geology of Petroleum, p. 34, 1925.

[2] Bull. Soc. Sci. Nat. Neuchatel, Vol. 7, p. 234, 1866.

[3] Petroleum and Its Products, 2d ed., Vol. 1, pp. 126, 142.

[4] Bull. California State Min. Bur. No. 19, p. 202.

[5] U. S. G. S. Bull. 653, 1917.

Algae, although not necessarily those forming the ordinary seaweed, have undoubtedly contributed a considerable amount to the formation of kerogen and oils. The evidence from fossil remains is extremely meager because of the absence of hard parts suitable for preservation in such organisms. The identification of algae remains in boghead cannels or torbanites by C. E. Bertrand and B. Renault,[1] while not direct proof of their occurrence in kerogens, does indicate the probability of such occurrence. The views of these men are sustained by the work of R. Thiessen,[2] but E. C. Jeffrey[3] considers the matter identified as algae to be the spores of vascular cryptogams.

Closely allied to the suggestion of the development of petroleum from the microscopic algae is that of its development from the diatom. Diatoms are microscopic plants of very wide occurrence, geographically and geologically. They are prominent in all Mesozoic and Tertiary ages, but are not definitely known in Paleozoic beds. The explanation of this lies probably in the alteration of the remains in these beds rather than absence in them originally. They are free-moving vegetable organisms dwelling in both fresh and marine waters. While of common occurrence in fresh water lakes and bogs, they seem to thrive best in marine waters. Unlike the algae they contain siliceous matter in addition to protoplasm or fleshy matter.

Beds in which the diatom remains are preserved are common in Tertiary strata and in some the amount of the diatom remains is such that the beds are known as diatomaceous shales. The Monterey and Tejon shales of California form the outstanding example of close relationship between oil producing sandstones and such shales. The beds of diatomaceous shale are nearly 2000 feet thick in some places, and their association with producing areas is so marked that many geologists have concluded that they were the source of the bulk of the oil in the San Joaquin Valley. Some have even concluded that the sections in which they are lacking will not be productive of oil.

Higher forms of plant life are considered by many to be of great importance. Theories in which such matter is considered as the source material are sharply divided according to the nature of the material used as the source. It is generally recognized that common cellulosic or woody material is too high in its content of oxygen to be considered as the source material of oils, unless a later process of partial decomposition with the removal of such matter be postulated. A number of writers have favored the coal distillation theory in which the oil was considered as having been formed by the natural destructive distillation of coal after it had been deeply buried. The observation of the formation of petroleum-like scums on the surface of peat bogs seemed to sustain this view. However, the identification of diatomaceous remains suggests them as a possible source of the oily matter in such places, instead of the cellulosic parts of the tree remains. In addition, while coal and oil deposits are found together in many localities and in rocks of the same geologic age, there is no apparent direct connection between them. The greater part of the oil produced in the Mid-Continent and Eastern provinces in the United States comes from areas in which the geographical association of coal and oil is marked. However, the oil producing horizons are largely of older age than the coal producing ones and are separated from them by a considerable thickness of impervious beds.

---

[1] Comp. Rend., Vol. 117, p. 593, 1893.

[2] U. S. G. S. Prof. Paper 132–I, 1925.

[3] Proc. Am. Acad. Arts and Sci., Vol. 46, p. 273, 1910.

The conditions in these and other areas indicate that there is no direct connection between the materials from which coal and oil have been formed after they have been covered over and removed from the zone of action of surface agencies. Assuming this, we are restricted to surface differences to explain the differences in the oil source materials. Two lines of explanation may be offered: first, if the higher forms of plant life are the original source, the differences between the source materials of coal and those of oil may be considered as having been brought about before the final deposition of those materials. This means that the cellulosic part of the vegetable matter must have been eliminated and only the resinous and other matter of low oxygen content have remained to be deposited in the latter case. The other explanation is that the same general type of material was laid down in both cases, but that the oil source materials were subjected to different types of surface alteration or decay.

In support of the first view may be mentioned the identification of numerous spores, pollens, and similar matter in the kerogen or oil shales of the Rocky Mountain states.[1] Such matter is of the type that might easily be separated by wind action from the cellulosic matter of the plants of which it originally formed a part. However, the identification of numerous partially decomposed plant fragments indicates

[1] Winchester, Dean E.: Oil Shale of the Rocky Mountain Region, U. S. G. S. Bull. 729, 1923.

that the separation was not complete, and that cellulosic matter was deposited along with the non-cellulosic pollens and spores. The evidence from these and other shales would indicate that differentiation proceeded during both the period of transportation and sedimentation and the interval following deposition but previous to covering.

Some of the material of kerogen shales may have been deposited in situ, but the general absence of remains of the larger parts of the plants from which the spores, pollens, and plant fragments could have been derived is a clear indication that the major portion was transported matter.

In this there is great similarity between kerogen shales and normal cannel coals, in which the presence of spore exines, resin lumps, and fragments of cuticle together with the general form of such deposits give good reason for considering them products of the deposition of material which had been transported for some distance. This is in marked contrast with the deposits of ordinary coal that are definitely known to be in situ deposits.

Comparative Importance of Different Materials.--The evidence supplied by observation of living organic matter, and the examination of fossil remains in strata associated with oil deposits, tend to indicate that attempts to imply that all such material was derived from a single family or group of organic life, or even exclusively from either plant or animal remains, are based upon insecure and inadequate evidence. At present the author feels that the weight of evidence available supports the contention that vegetable matter is the major source of the world's petroleum but does not believe that it can be considered as the exclusive source. The relative importance of different types of plants is open to discussion. In some places it would appear that one may predominate almost to the exclusion of the others. In another, two or more may contribute almost equally to the accumulation of organic debris.

Manner of Deposition and Accumulation.—The aquatic nature of the life from which the oil source materials were derived seems to be generally conceded. With the exception of the spores, pollens, and fragmental products that may have been derived from life along the shore and in low lying swamps, the material mentioned is solely that of water bodies. As to whether the water bodies in which the deposition finally occurred were fresh or saline, the evidence is less definite. While diatomaceous and foraminiferal oozes are now forming at great distances from land, it would appear that the deposits that have contributed the most to the formation of oil were laid down in waters of moderate or even shallow depths. One indication of this is the interbedding of sands, some being of cross-bedded type, with many of the black shales considered as the source materials of the oils in those sands. The general limitation of fishes and other higher forms of marine life to coastal areas, because of the greater amounts of food present, was probably as important in the past as it is today. The higher types of plants are very definitely restricted to land surfaces, swamps, lagoons, and similar shallow water bodies.

The common association of salt water with oil has led to the wide acceptance of the belief that salt water is essential to the formation of oil. Different functions are ascribed to the salt water by different writers. One of the earliest of these, C. Ochsenius,[1] considered that petroleum was formed from marine organisms buried beneath air-tight sediments that were slowly acted upon by the concentrated brines, which accumulated during the last stages of evaporation of sea water. According to Ochsenius the active substance in these brines buried with the organic remains was magnesium chloride. There seems to be little evidence to support this contention or the views of others who consider other ingredients as the active agencies of generation.

R. Zaloziecki[2] considered the function of the salts of the sea water to be that of retarding and modifying the decay of animal matter on or near the sea shore and giving adequate time for its transformation into petroleum. This suggestion that petroleum is the direct pròduct of a special type of putrefaction carried on under the modifying influence of marine waters has received considerable support. The evidence offered is that oils or bitumens are being formed on the mud surface of the small bays of the Red Sea, along the shores of the Dead Sea, in the salt marshes of Sardinia, and near land along the coast of Sweden. Murray Stuart,[3] one of the supporters of the theory, in reply to the objection that the oil would be rapidly disseminated over the surface of the water, points out that small particles of clay and detritus have a marked affinity for minute globules of oil and would hold most of them to the bottom until they were covered over by later deposits.

[1] Chem. Zeitung, Vol. 15, p. 935, 1891; and Zeitschr. Deutsch. geol. Gesell., Vol. 48, p. 239, 1896.

[2] Chem. Zeitung, Vol. 15, p. 1203, 1891.

[3] India Geol. Survey Rec., Vol. 40, pp. 320–333, 1910; Inst. of Pet. Tech. Bull., Vol. 12, pp. 316–335, 1926; The Geology of Oil, Oil Shale, and Coal, 1926.

There seems to be a more general feeling, especially among American geologists, that the function of the water covering is merely that of retarding and modifying the decomposition of the organic matter, and that the evidence does not warrant the assumption that petroleum is created directly by putrefactive action. It seems to be generally conceded that salt water is a better medium than fresh water for the precipitation of clays and organic debris and for the preservation of such material until covering takes place.

Microscopic studies of the nature of kerogen have, because of the identification of land fauna, particularly in the Green River shales of the Rockies, led to the assumption that they were deposited in fresh water lagoons and shallow lakes rather than in marine waters. Some students have inferred that this is the reason the kerogen has remained as such and not been converted into petroleum. This view is not sufficiently supported at present. Later studies have led to doubt as to whether the Green River shales were actually deposited in a strictly fresh water. Junius Henderson[1] suggests the possibility of a moderately salt water.

While the evidence generally favors the deposition of petroleum source materials in waters of marine nature and doubt has thus been cast upon the fresh water origin of the often cited Green River shales, the assumption that salt water is essential to the deposition of oil source materials does not appear to be warranted. That it assists materially would probably be generally admitted.

Anerobic Bacterial Action.—Both geologists, who consider that petroleum is derived directly from organic matter by putrefactive action and those who consider such action as merely a stage in a longer process of conversion, attach great importance to work of bacteria between the time of deposition and burial. Normal decay, that is, decay in which the substance is exposed to the atmosphere, is caused largely by aerobic bacteria. As these utilize the easily accessible oxygen of the atmosphere, decay proceeds fairly evenly regardless of composition of the substance attacked, whether cellulosic or non-cellulosic. Decay under a cover of water must be accomplished in the absence of free oxygen. The prominence of anerobic bacteria, those capable of extracting the oxygen of the cellulose, ligno-cellulose, and other organic compounds high in oxygen, is obvious. The natural result of such bacterial action is the indefinite preservation of substances low or entirely lacking in oxygen, while those which are high in that element are attacked and destroyed or converted into substances of low oxygen content.

---

[1] Am. Assoc. of Pet. Geol., Vol. 8, pp. 662–668, 1924.

This may account for the high degree of preservation of many spores, seeds, pollens, cuticles, certain types of leaves, and stems in carbonaceous shales of Colorado, Kentucky, and northern Texas.

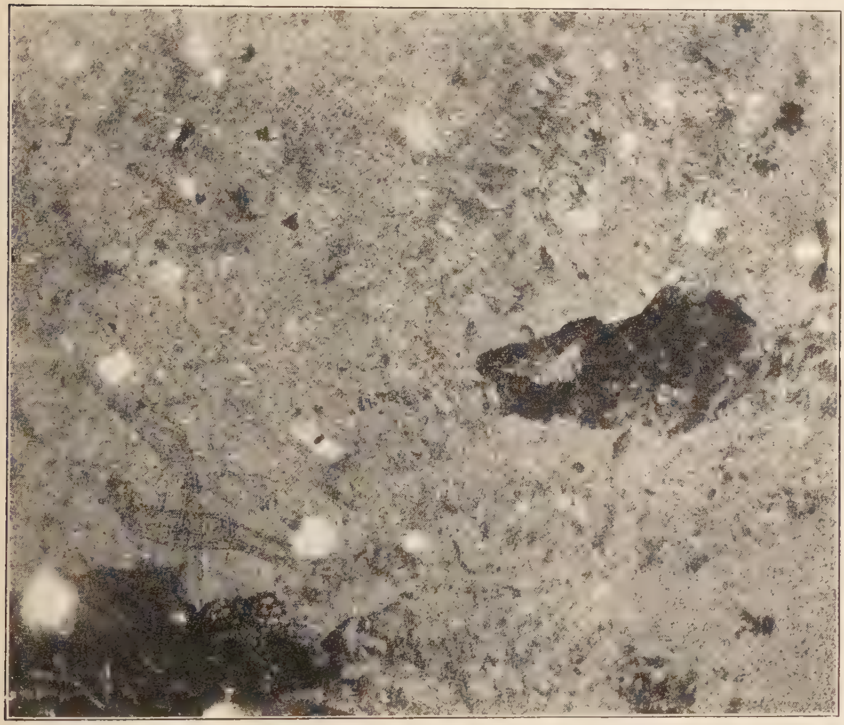


Fig. 4.—Microsection in horizontal direction of an oil shale from the Green River formation of Colorado. Photomicrograph by W. H. Bradley. Courtesy U. S. Geological Survey.

Less is known of the origin of the organic ground mass which forms the matrix for these substances. Colin C. Rae[1] suggests that this is a substance of more complete decomposition, possibly an ulmo-humic one. While possibly of different nature than suggested by Rae, the suggestion appears to be entirely logical.

The mixture of plant and animal debris, partly so decomposed as to be unrecognizable under the microscope and partly still largely unaltered and retaining much of its original structural form, is subject to the action of surface agencies and especially of bacteria as long as it is not completely covered by impervious clays or similar materials. A. B. Thompson[1] suggests that colloidal enzymes from anerobic bacterial action may act as catalysts in causing further reaction after burial. In general, however, burial is considered to end the period of alteration of the organic debris by surface agencies. David White[2] calls this the period or stage of "Biochemical" action to distinguish it from the later stages in which different agencies of alteration are active. The latter he calls the "Geochemical" stage. The organic matter at the end of the stage of biochemical alteration is called sapropel by some authors; and the clay which contains it, sapropelic clay.

---

[1] Am. Assoc. of Pet. Geol., Vol. 6, p. 340, 1922.

The Nature and Alteration of Kerogen.—Stuart[3] and others who support the theory that oil is a direct product of putrefaction consider that the oil is merely held in intimate association with the particles of the clay in which it is interbedded. The creation of free oil calls merely for the breaking down of the adhesion between the clay particles and the oil and the movement of the oil into a more porous medium in which it can circulate freely. If the condition postulated be accepted, it is reasonable to expect that expulsion might easily be accomplished by the agency of pressure alone. That pore space decreases as clays are converted by pressure into shales, and the lighter and more porous rocks into heavier and more dense products, is well known. The expulsion of oil is then mainly a physical process.

If the putrefactive generation of oil is not accepted, the nature of the kerogen and the manner of its conversion into oil become of greater interest. The limited recovery of oil by solvents as shown on page 46, compared with the amount recovered after the shale has been subjected to heat, seems to indicate that there is a definite chemical change when kerogen is converted into oil. Certainly the general insolubility is indicative of the absence of free oils in quantity in most shales. The occurrence of limited amounts of oil as shown by the solvents appears to be in keeping with the suggestion that oil is the product of the gradual alteration of a substance which is not itself an oil.

The possibility of converting this substance, kerogen, into oil by heat has not only been demonstrated in the laboratory but is the

[1] Oilfield Development, pp. 271–272, 1916.

[2] Proc. Geol. Soc. Amer., Vol. 28, pp. 727–734, 1917.

[3] See page 87.

basis of a substantial industry in Scotland and has been used in other areas at various times. That oil may be generated by pressure alone seems to have been proved by A. W. McCoy and Earl A. Trager. The description of their experiment as given by McCoy[1] is of sufficient importance to quote:

"Description of flowage experiment,—Cylindrical steel bars were sawed into lengths of about three inches and bored into tubes having an inside diameter of 2 c. m. The thickness of the walls in the center of the cylinders was reduced to 0.25 c. m. Pistons of steel were turned to fit the tubes. Cylindrical pieces of oil shale (yielding 25 gallons per ton and having a crushing strength of about 3000 pounds per square inch) were cut into one inch lengths and placed in the center of the tubes where the thickness of the walls was reduced. The pistons were then inserted on either side of the shale cylinder and pressure was applied to them in a Riehe compression machine, thus squeezing the shale and eventually bulging the tubes in the center. By so doing, the shale was made to flow. No appreciable amount of heat was developed. Solution tests taken before the experiment gave no indication of liquid hydrocarbons, while those taken after the

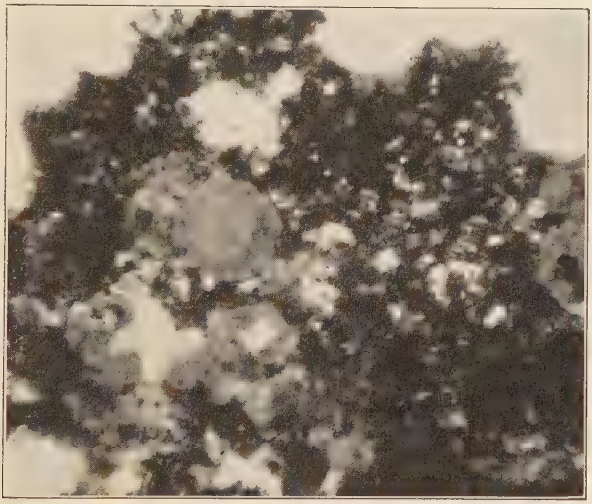


FIG. 5.—Microsection in horizontal direction of a spore-bearing Devonian black shale from Ohio. Photomicrograph by T. Stadnichenko. Courtesy U. S. Geological Survey.

---

[1] Jour. Geol., Vol. 27, p. 252, 1919.

flowage with the same shale gave strong coloration. In some cases, after the experiment small globules of oil could be seen in the shale with a hand lens. The steel tubes necessitated such great pressure to make the bulging that tubes of brass and softer metals were tried. The results were substantially the same.''

In another report of the experiment Trager[1] concludes that kerogen can be converted into oil either by the aid of heat, or by pressure. In the latter case, the pressure must be of such nature as to allow molecular displacement.

In the conversion of kerogen into oil in nature, it would appear that greater importance might be attached to dynamic pressure than to static pressure. The latter alone, if sufficiently large because of the great thickness of overburden above the kerogen containing bed, might cause sufficient rearrangement of the kaolin grains and other inorganic and, generally speaking, relatively incompressible matter as to subject the kerogen to intense pressure. The ability of the dynamic forces, working horizontally in conjunction with static pressure to alter sediments completely, is fully demonstrated by the condition of metamorphic rocks derived from such sediments. It would seem probable that the same agencies might at an early stage cause sufficient reduction of the pore space as to bring the kerogen under pressure and cause its alteration and expulsion as an oil.

While McCoy reports no appreciable increase in temperature during the flowage experiment, such increase would be natural, and in the case of movements within the earth likely to be considerable. Bailey Willis[2] suggests that the maximum temperature attained in the lowest strata of the Appalachian geosyncline was not over 200° C. Even this limit is considerably higher than any of the temperatures observed in producing fields. If applied for long periods with high pressures, it might well accomplish the same result as is obtained with higher temperatures of short duration in the laboratory.

While there is no evidence available to give an indication of its quantitative importance, it would appear logical to expect that water associated with sapropelic matter in the original clay, or the water, which was probably produced as a dehydration product in the early stages of the alteration of sapropelic matter, just as it is in the alteration of peats, would be of major importance in the creation and expulsion of the oil. Its greater capillary strength would materially

[1] Amer. Assoc. Pet. Geol., Vol. 8, p. 310, 1924.

[2] A. I. M. E. Bull. 157, Sec. 10, pp. 1–7, 1920.

assist in the forcing of the oils into the larger pores of adjacent sandstones and other reservoirs.

Data concerning the nature of the oil created in the kerogen by dynamic pressure are entirely lacking. The drops of oil referred to by McCoy were not sufficient in amount to permit analysis. Differences in the nature of the compounds obtained by retorting or destructively distilling shales can hardly be considered as indicating the nature of the oils formed by dynamic pressure except in a most general way. It would appear that there are two stages in the process of converting kerogen into oils by heat. In the first, the kerogen is converted into bitumen; in the second, the bitumen is changed into oil and gas vapors and carbon. The first begins at much lower temperatures than the second. There is reason to believe that the substances produced in the first stages are products that vary only slightly from the original kerogen matter and that the development of the wide variety of individual compounds is the result of cracking of these complex and unstable original bitumens.

In the laboratory and the shale oil retort, these reactions go on simultaneously, making it difficult to interpret the action during each stage. While different conditions might apply in different areas, it appears logical to expect that in the natural conversion of kerogen, where pressure is the chief agency, the two stages would occur at somewhat different times. The total separation of the two stages hardly seems probable as there is ample evidence to indicate that kerogen is not all of the same chemical nature and decomposes at widely different temperatures.

While the application of pressure in nature would be slow compared with the application of heat in the laboratory or retort, there is no reason to expect that the chemical composition of the oil moving from the shale into the porous rocks adjacent to it would be identical with that of the original kerogen. Cracking, with the simplification of molecular structure and reduction of the amount of unstable matter through separation and deposition of part of the original carbon, would probably occur during the conversion of kerogen into bitumen and the alteration of that bitumen as it passed through the shale pores toward the porous rocks. This is indicated by the occurrence of natural gas with all oils, including even the heaviest and most viscous types, and by the presence of residual elemental carbon in shales similar to those still containing kerogen matter. The spent or true carbonaceous shale remaining is of no commercial interest; but partly spent shales, in which only part of the kerogen has been altered, may be of importance. The Devonian black shales of the Ohio Valley are probably in the class of partly spent shales. Shales in the metamorphosed areas of eastern Pennsylvania and New York are almost completely spent.

Nature of Oils.—According to the process of formation just outlined, oils, while differing to some extent, were probably largely nonvolatile types of high density and viscosity at the time of their creation and expulsion from the shales. Differences in the nature of the source materials and in the conditions surrounding the creation and expulsion of the oils must be given some importance, but they cannot be considered as satisfactory explanations of such wide differences as occur between the 12° Baume oil of the Panuco pool in Mexico and the 61° Baume oil of the Hogback pool in northwestern New Mexico. In addition, the oils produced by retorting shales are not comparable with the light paraffin base types but approach the light asphaltic and the heavy mixed base types in many respects.

The lighter and more volatile petroleums differ from the normal heavy oils (those composed essentially of hydrocarbons as against those containing large amounts of sulphur and oxygen) chiefly in the less complex structure of the hydrocarbon molecules of which they are composed and in the higher ratio of hydrogen to carbon in those molecules. Such differences may be considered as having been produced in one of three ways: first, by hydrogenation of the hydrocarbons; second, by removal of the heavy compounds existing in the original mixture; and lastly, by alteration of the compounds already existing with the freeing and removal of elemental carbon.

Hydrogenation of Oils.—The addition of hydrogen to the unsaturated hydrocarbon molecule is possible under certain specified conditions. However, there is no evidence of the presence of appreciable quantities of free hydrogen in the gases normally associated with oils. Its existence in "dry gases," where oil does not accompany it, may more logically be considered as due to the decomposition of hydrocarbon compounds.

Removal of Heavy Compounds.—The heaviest types of crude oils contain lighter constituents which are of low viscosities and boiling points compared with the rest of oil. D. T. Day[1] pointed out that the separation of petroleum into fractions differing in density and viscosity is accomplished by filtering crude oils through Fuller's earth. The reaction is now widely used in removing coloring matter in lubricating oils and waxes in the refinery. Day was sufficiently impressed with the changes in the character of oils caused by Fuller's earth to suggest that Pennsylvania oil had at some time in the past possessed properties very similar to those of the Ohio oils, but that in its migration to its present abode from lower strata its character had been changed. Experiments carried on in the laboratories of the United States Geological Survey indicated that other clays had properties similar to those of Fuller's earth.

---

[1] Science, new series, Vol. 17, pp. 1007–1008, 1903.

The movement of oil occurs more commonly in porous sandstones and limestones than it does in clays and shales. Experiments carried on by Gilpin and Bransky[1] showed no fractionation in the gravitational diffusion of oils through sands and limes. Experiments by the author indicate that the forcing of oils through sands under hydraulic pressure similarly causes no alteration in the nature of the oil.

Closely allied with the suggestion of the retarding of the movement of the more viscous constituents is the suggestion that the less viscous would be more easily carried along by gas migrating up the slope of a porous sandstone than the more viscous and less volatile constituents. That such action does occur is indicated by numerous observations on the nature of casinghead gases. Such action is similar to the action of the automobile carburetor and depends largely upon the velocity of the gases passing over or by the oils. In the escape of gases from high pressure oil and gas wells, the amount of oil carried in this way may be large. It is questionable whether the velocities of gases in the sands ever reach the velocities necessary for such action before the creation of the vent in the form of the oil well.

Diffusion through clays having adsorptive qualities, the selective action of moving gases, or the selective action of moving water, which is considered by some as being an important agency in the accumulation of oil in structures, may all be considered as tending to modify the nature of particular oils; but there does not appear to be any evidence to warrant giving them a position of major importance. Certainly they must have been of minor importance in non-outcropping lenticular sand bodies such as occur in every large field.

Internal Alteration of Hydrocarbons.—It seems necessary to conclude that changes in the internal structure of the hydrocarbons are responsible for the conversion of oils of low rank into those of high rank and low density. The conversion of the heavier and less volatile members of the olefine and naphthene families into lighter and more volatile members may be accomplished without alteration in the ratio of hydrogen to carbon. The conversion of unsaturated types into saturated types, with the exception of the conversion of olefines to naphthenes, is accompanied by an increase in the ratio of hydrogen atoms to carbon atoms. As hydrogenation is not probable, the only remaining possibility is that carbon has been given up by the hydrocarbons in the conversion. The rapid accumulation of carbon in the bottom of the cracking still or cracking chamber of the refinery is adequate proof that the separation of carbon is likely to occur in the formation of the simpler and more completely saturated hydrocarbons. The prominence of methane gas as a byproduct of the same reactions seems to indicate that this, being the most stable and saturated of all of the hydrocarbons, is the one most easily produced.

---

[1] Gilpin, J. E., and Bransky, O. E.: U. S. G. S. Bull. 475, 1911.

Cracking in the refinery is accomplished with the oil in the form of a vapor, a liquid, or a combination of the two. The pressures used in the refinery cracking still are greatly exceeded by those in nature, but the temperature of the cracking unit is not approached. Time is known to be an important factor in the development of saturated and stable compounds in the refinery cracking unit. The time available there is infinitesimal compared with that available for natural cracking processes. Catalytic agents, such as nickel and anhydrous aluminum chloride, are considered as of major importance by some; but commercial cracking processes of the present time give little or no importance to the catalyst.

The relative importance of the agencies that might be postulated as affecting the natural cracking processes which have operated upon the oils contained in the crust of the earth can only be inferred in a rough way. Certainly temperature holds a much less important position than it does in refinery cracking. The function of time is not clearly defined. The lower average density and greater average volatility of the older oils is well known. Within the United States, Tertiary oils are found to be heavier than Cretaceous; and Cretaceous, heavier than Paleozoic. Within the Paleozoic, however, there are wide differences in character, oils of the Ordovician and Silurian ages in the Eastern province having a higher average density than those produced from Devonian and Mississippian beds. If "aging" is the most important of agencies causing alteration of lower into higher hydrocarbons, it would seem that all oils, unless abnormal in composition because of the presence of sulphur or other elements, should be of the same character if of the same age regardless of the conditions and localities in which they are found. A comparison of this type made by the author in 1921 shows the absence of such relationship for Pennsylvanian oils found in the central and eastern parts of the United States. Similar and possibly greater differences could be found by extending the study to include other areas and other ages.

TABLE 28.—COMPARISON OF PENNSYLVANIAN OILS.

State	Number of Analyses	Average Baume Gravity
Oklahoma	28	35.1
Kansas	18	33.9
Illinois	18	31.8
Ohio	5	45.1
West Virginia	29	42.2
Arkansas	gas only	—

The pressures bearing upon the oil in a porous container are of several types according to their origin. Basically the division is into pressures of movement or dynamic pressures, and stationary or static pressures. The latter are caused primarily by the weight of the sediments overlying the oil-containing beds, and the former by crustal movements. The force of either affecting the hydrocarbons of the oil bearing strata depends largely upon the condition of that horizon. If composed of coarse irregular grains with sufficient cement to prevent readjustment of the grains and the creation of smaller pore spaces, the pressure actually placed upon the oil contained may be relatively small. If the sand is loosely packed and devoid of cement, a rapid reduction in the pore space and the placing of the oil under considerable pressure at an early stage may be anticipated. The development of effective pressure in lenticular bodies completely saturated with oil and brine may be anticipated before that in larger bodies, which are only partly saturated or have access to the surface. Capillary phenomena and hydraulic pressures probably are important in such cases in preventing free movement and the loss of effective pressure.

"The deeper the sand the better the oil" is a common expression in the oil fields. Recent developments in California, where deep sands contain oil of 28 to 35° Baume gravity while the shallow productive horizons in the same pools yield oils of 18 to 20° Baume, support this theory. Similarly in Oklahoma the 40° Baume oil of the "Wilcox" series is frequently obtained by deepening wells which produce 30° Baume oil in the shallower Dutcher horizon. Decrease in density, however, does not progress regularly with increase in depth. In some cases the decrease not only stops, but the deeper oil is heavier than that above it. Thus at Long Beach in California oil of 22° Baume is found at 4700 feet while oil of 26° Baume is obtained at 3500 feet. If a comparison of oils found at the same depths in different areas be made, the lack of general application becomes more apparent.

If dynamic pressure be considered as the force causing alteration, the differences in the character of the evidence become less conflicting. Differences in the degree of effectiveness of such pressure upon oils, due to differences in the physical characteristics of the media containing them, may cause differences such as that referred to at Long Beach. That such differences may be caused by interaction with substances in solution in oilfield waters will be shown later. Without static pressure derived from a thick covering of overburden, dynamic pressure would be able to accomplish little. The thrusts that cause intergranular movements and the development of frictional heat and effective pressure in the deeper horizons cause buckling or folding of the beds where static pressure is small. In such movement, there is little or no pressure actually applied to the imprisoned oil.

The most striking example of increase in the degree of alteration with approach toward the center of dynamic movement is found in the Paleozoic oils of the Appalachian field and related fields to the west. Dry gas composed mainly of methane, the most stable of the hydrocarbons, forms a belt east of the oil-containing belt and nearest the centers of the dynamic pressure, which caused the building of the Appalachian Mountains. The gas belt is at right angles to the direction of the lines of force. Oils of the same age are progressively lower in grade as one proceeds westward, but in no section has dynamic pressure failed to have some effect. The same condition is found to exist in the Pennsylvanian horizons of the Mid-Continent area where gas is produced along the Oklahoma-Arkansas line; high rank oils, in the eastern part of Oklahoma; and typical mixed base types, farther west in the vicinity of Tulsa, Sapulpa, and Bristow.

The areas cited as examples also produce oils from deeper horizons which have been subjected to alteration previous to the deposition of the younger and shallower horizons. Thus a map that showed the density or Baume gravity of all oils produced in Oklahoma or in Pennsylvania might indicate but little concerning the relationship between the center of dynamic force and the character of the oil resulting. A difference of three or four hundred feet in the depths of two horizons productive in the same locality is not adequate explanation of an increase of ten degrees Baume in the gravity of the lower over the upper oil. In the absence of striking differences in the nature of the containing media, one is inclined to suggest the possibility of differences in history between the upper and lower horizons. In the Paleozoic areas mentioned, a marked decrease in density is indicative of transition from rocks of one age to those of an earlier period separated from the overlying ones by an unconformity. The unconformity is indicative of crustal movement and probable alteration of the oil in the rocks below previous to the deposition of those above.

Carbomorphism of Coals.—Probably the best evidence supporting the theory of progressive alteration of hydrocarbon matter through the action of dynamic forces within the earth is that given by the alteration of coal by the same agencies. The depositional period of coal formation differs from that of the oil source materials. In the former, accumulation undoubtedly took place in a low lying swamp below whose waters all types of life were submerged indiscriminately. The stagnant waters protected both cellulosic and non-cellulosic matter alike. The predominance of the former can be ascribed to the solid nature of the product. Subjected to dynamic forces of alteration, after a period of covering during which subsequent deposition gave the necessary static pressure, it shows changes similar to those outlined for the kerogen-oil series. The major difference lies in the fact that the escaping products of the reactions in coal are not of commercial interest, while those produced in the alteration of kerogen are liquid petroleums, and the alteration products of the heavier types of oils are the more valuable and desirable types of oils. The chief products of the alteration of coals are water, carbon dioxide, and methane. The first two are not of commercial interest, and the last is not present in sufficient amounts to be of value.

In the coal series as a whole, there is no break in the gradation extending from the uncovered peat in the peat bog to the seam of graphitic anthracite. Coal beds of Pennsylvanian age east of the Mississippi show a very definite decrease in the degree of their alteration toward the west and away from the center of dynamic pressure causing the Appalachian folding. The coals of Illinois, Ohio, Indiana, Michigan, and western Kentucky are typical non-coking low rank bituminous coals; those of western Pennsylvania and western West Virginia are coals of coking grade, which yield large amounts of volatile matter and gases; and those of the eastern edge or portion of the Appalachian coal field are non-volatile coking types and high class steam coals of semi-bituminous rank. Erosion has removed the coal measures which probably formerly covered the center of Pennsylvania, but in the eastern part of the state and nearer to the centers of dynamic pressure true anthracites are found. If the study be carried still farther to the east, one finds the graphitic anthracite of Rhode Island. The transition in the inorganic rocks is no less marked, the soft shales and porous sandstones of Illinois being replaced by metamorphic slates, gneisses and schists in the east.

While the problem is somewhat complicated by the introduction of igneous activity, the Cretaceous coals of the Rocky Mountains and Western Plains show the same progressive increase in alteration with approach toward the centers of crustal disturbance. The coals are of semi-bituminous rank in the most affected areas, while black to brown lignites are found in the least affected.

Destruction of Hydrocarbons.—If abnormally high temperatures are used in the refinery cracking unit, an excessive amount of fixed gases is produced. Methane is the most important of these, but hydrogen is a notable constituent in some cases. It is probable that in the natural alteration of hydrocarbons some are completely broken down with the evolution of hydrogen and the deposition of residual carbon. However, the percentage of hydrogen reported in natural gases is small. This may be due to the low atomic weight and high molecular velocity of hydrogen, which tend to make its retention in rocks more difficult than the retention of methane or ethane. Otherwise it would be difficult to understand the entire lack of natural gas in central and eastern Pennsylvania, sections in which the rocks are identical in age with those containing gas and oil in the western part of the same state. Mere expulsion of methane and other hydrocarbons through the agency of increasing pressure is hardly sufficient to explain this absence, especially in deeply buried lenticular horizons.

Effects of Sulphur on Oils. Undoubtedly a considerable proportion of the sulphur contained in petroleum is indigenous with it in origin. Such sulphur may be considered as being derived from the animal and plant remains which furnished the carbon and hydrogen. Sulphur is a constituent of practically all of the higher forms of life; but like nitrogen and oxygen, is subject to diminution in the process of decay through which the petroleum source materials pass. W. H. Emmons[1] attributes a part of the sulphur to the action of sulphur bacteria in taking sulphates present in marine waters and setting the sulphur free. While the sulphur content of many oils may be attributed to such action, it would appear necessary to look to other causes for explanation of the wide range of percentages present in different oils, some of which are closely related geographically and geologically. Examination of the waters of the San Joaquin Valley indicates marked differences between the percentage of sulphate present in the deep waters associated with oil and those containing no oil. The low percentage of sulphate in the former as compared with the latter is accompanied by a large percentage of carbonate and some indication of the presence of sulphides. While the reactions have not been worked out, it appears that the sulphates in the water have been reduced by interaction with the hydrocarbons, and partly converted into carbonates. The sulphur from the sulphates appears to have been added to the oils in the form of free sulphur, the sulphide, or the sulphate radicle. The sulphate content of waters from wells in the Appalachian oil producing areas is similarly low.

---

[1] Geology of Petroleum, p. 85, 1921.

Where oils are of unusually high density and show a large amount of sulphur, the interaction of oils and sulphate solutions seems to be fully sustained. In California differences in gravity between oils found in the upper portions of structures and those found on the edges in contact with water are marked. In some places the interaction with associated waters has led to the development of a semisolid substance called tar. In the Tampico-Tuxpam area of Mexico and in other areas similar to it, the possibility of alteration of oils by the agency of sulphur containing solutions or gases of solfataric origin must be recognized. Hydrogen sulphide and sulphur dioxide are common constituents of gases of magmatic origin. In Mexico the abundance of igneous dikes, basaltic plugs, and sills, together with the abundance of fracture planes is indicative of the intensity of igneous activity. The high porosity and cavernous nature of the limestones in which oil is generally found promote rapid and thorough diffusion of those gases.

The introduction of sulphur, or of sulphur and oxygen, through reactions between oils and associated waters has a material effect upon the character of the oil. Where the oils are light, the saturated character of the compounds tends to retard the combination. Where composed largely of unsaturated compounds, the reactions are apt to proceed on a large scale and a considerable quantity of sulphur be taken up by the oil. As indicated in Chapter II, this increases the viscosity and the density of the oil. The oil that contains sulphur is invariably of higher density than the one that does not, although the two may be found in the same area and have been subjected to the same degree of dynamic alteration.

Conversion of Oils to Solids.—Wherever oil and gas are imprisoned in porous rocks having access to the surface, it may be expected that they will tend to move toward that surface. Such movements are the logical result of the physical properties of these substances and are materially encouraged by the circulation of ground waters. The gas or oil seepage can be held responsible for the loss of enormous quantities of these substances during the space of geologic time. Not all of the hydrocarbon matter escapes in this way. Neither is it all left as oil, nor is it all destroyed. A substantial portion is converted into other substances closely related to oils.

The conversion of liquid hydrocarbons in solids may be accomplished in three different ways or by a combination of the three processes. First, it may result from the addition to the hydrocarbon molecule of a new and foreign element to produce a product of different physical nature. Secondly, it may be accomplished by the escape of the more volatile fractions, leaving behind only the solid hydrocarbons which were dissolved in the original hydrocarbon solution. Lastly, it may be the product of change in the internal structure of the molecule itself.

The discoloration of many refined oils, left in tightly sealed bottles, on exposure to the sun light is ample evidence that polymerization or internal rearrangement of the molecules does take place. The product in such cases is frequently of higher viscosity than the original substance. Reactions of this type are most common in the heavier fractions of asphaltic oils in which the content of unsaturated hydrocarbons is high. It seems logical to assume that similar alteration will occur in oils rising to the surface at seepages. The author knows of no way of gauging the influence of such reactions upon deeply buried oils. He is inclined to believe it of minor importance, and that the major tendency in most of such reactions is toward a decrease of viscosity.

Greater importance should probably be attached to theories attributing the solids to the escape of the more volatile fractions of the liquid. The escape of such fractions is generally due to evaporation. While the evaporation of gasoline and kerosene hydrocarbons from surface pools of seepage oil under the direct heat of the sun is easily understood, it is questionable whether such evaporation can account for all residual hydrocarbon deposits. The deposition of paraffin wax on pumping rods and tubing and in the bottom of oil wells cannot be said to be due to evaporation. It might rather be considered as due to decreased carrying power of the solvent liquid with decrease in temperature and pressure on leaving the pore spaces of the rock and entering the open well. The paraffin or ozokerite veins of Galicia, Burma, Utah, and other areas are probably of related origin. Such veins are known to depths of 2000 feet at Boryslaw in Galicia. Close to the surface the sandstones in the same region are impregnated with wax, forming natural wax or ozokerite sandstones.

While the content of volatile constituents is extremely low, there is reason to believe that the tar sands or bituminous sandstones which outcrop in the Athabasca district in Alberta and parts of Kentucky are residual oil horizons. Adhesion undoubtedly caused the slowing up of the movement of the oils toward the outcrop and its retention in the pores of the sands, while the more volatile portions were atomized and drawn along by escaping gases. The escape of the more volatile and less viscous materials may have been accomplished by converting them to vapors, or by moving them along as liquids after the more viscous portions had congealed and separated out.

The transformation of petroleum into a solid by the loss of the more volatile constituents may be considered as a satisfactory explanation as long as the product is composed essentially of hydrocarbons. In most of the asphaltic rocks, asphaltites and true asphalts, the analyses show large amounts of sulphur. In some oxygen is also important. In such instances the influence of extraneous matter, especially that containing sulphur, is of prime importance. The prevalence of asphalt deposits in contrast with the limited occurrence of paraffin solids and mixtures of the two types leads to the conclusion that differences in the nature of the oils from which they were derived play an important part in the formation of solids.

The unsaturated and therefore more easily attacked compounds are common in the asphaltic oils but not in the paraffin types. Such compounds are readily attacked by sulphur-containing compounds in magmatic waters and gases. They are subject to complete alteration by the oxidizing action of surface waters and to union with the sulphur of the sulphate radicle contained in such waters. The widespread occurrence of tar sands as replacement products of oil in the shallow horizons of the Valley Field of California, where it is in contact with surface waters, is undoubtedly the result of such reactions. Between the tar and the true oil is a tarry oil which commonly characterizes the oil and water contacts in many horizons. The water close to the contact differs materially from that at a distance.

Suphur bearing compounds react with saturated hydrocarbons also, but the reactions are slower. In addition, with the exception of a few cases, some of which are questionable, paraffin oils are contained in horizons in which meteoric waters have not gained entrance and no renewal of the original sulphate content by the introduction of fresh surface waters has taken place. The amount of sulphate available for reaction with the oils in the present productive horizons in Pennsylvania has never been as great as that in the Valley Field of California.

Pyrobitumens. —The relationship of the pyrobitumens, which are insoluble in petroleum solvents, to those substances which are soluble is not clear. Some authors consider that they are oxidation products; others, that they are direct residues from the partial distillation of petroleum, differing only slightly from the ordinary petroleum bitumen in the manner of their formation. The writer personally feels that the product of either type of reaction would not differ materially from the ordinary petroleum bitumen, and that true pyrobitumens, such as albertite and wurtzilite, are products of the alteration of petroleum bitumens by dynamic or contact metamorphism. The nature of that reaction is, however, undetermined.

Summary. -The problem of the origin of petroleum and its allied substances still remains one about which we have much to learn. Theories relying upon inorganic phenomena appear to be no longer tenable as explanations of the occurrence of oil and gas in areas in which they are present in commercial quantities. Geologists and chemists are generally agreed that the original source material was organic in character. Agreement beyond that point is not indicated by the opinions expressed in geologic literature. Some strongly advocate animal source materials; others, plant remains. A growing number consider that both sources have contributed, and that the proportions of each and of the different types of life within each group have varied in different places.

The manner of transportation, deposition, and preservation of the organic debris is a subject of debate. Probably the greatest controversy centers around the nature of the connecting link between the organic debris and the oil. Murray Stuart[1] and several other English geologists consider that the organic matter was converted into oil prior to its burial in those areas where it has formed free oil. They believe the formation of free oil is largely a process of breaking down the adhesion of oil for clay particles and expelling the oil to the more porous rocks. Stuart considers the kerogen or oil shale to be the product of the burial of organic matter which has not been converted into oil, and believes that such shales can never be considered as the source of free oils.

The majority of American geologists consider the chemical action up to the time of burial as instrumental only in creating a substance of low oxygen content from which oil may be generated by heat or pressure, or both, at a later date. To them kerogen is an intermediate substance in the alteration of organic matter to petroleum. They believe that definite chemical changes must occur before it can be converted into free oil.

One English geologist, Cunningham-Craig,[2] has concluded that kerogen is neither a stage in the development of petroleum nor a substance in a parallel series. He has advanced the theory that kerogen shale is the end product of the adsorption and absorption of free oil by argillaceous matter.

The author believes that the evidence distinctly favors the view that kerogen is an intermediate substance between the organic debris and the petroleum, and that its conversion into the latter calls for chemical and physical changes. These may be brought about by forces available within the crust of the earth. The nature of the oil formed in this manner will vary somewhat with the chemical nature of the original source materials and with the manner of application of the forces causing its generation, but it appears to be of rather viscous and heavy nature and to contain substantial percentages of unstable compounds. Its subsequent alteration is determined by the nature of the agencies which affect it. It may, through interaction with the sulphur and other active ingredients contained in the substances with which it comes in contact, become heavier and more viscous and gradually be converted into a solid of asphaltic nature. In other cases it may be subjected to processes of dynamic alteration and change into a more stable and lighter type of oil. Ultimately it may be converted into a gas or entirely destroyed. In some cases it may be subjected to a combination of altering factors and give rise to other products such as ozokerites or pyrobitumens.

---

[1] Stuart, Murray: The Geology of Oil, Oil Shale, and Coal, 1926; also Inst. of Pet. Tech., Vol. 12, No. 56, pp. 316–335, 1926.

[2] Cunningham-Craig, E. H.: Kerogen and Kerogen Shales, Jour. Inst. Pet. Tech., Vol. 2, pp. 238–269, 1916.

The discussion of the alteration and destruction of petroleum has been based upon the assumption that the view of its formation from kerogen was essentially correct. Considerable modification would be necessary if new evidence were discovered, which would make it necessary to revise the views of the nature of kerogen which have been accepted.

CHAPTER V.

FUNDAMENTAL GEOLOGIC CONDITIONS LIMITING THE OCCURRENCE OF PETROLEUM.

The previous chapter discussed briefly fundamental questions relating to the manner of formation, alteration and destruction of oil and its related substances. Such discussions may be carried on merely from the standpoint of scientific interest. The amount of time and energy given to such discussions by individuals and corporations, which are interested primarily in economic returns, indicates that in more complete understanding of the origin of oil there are possibilities of greater financial returns. The theories are based upon, and supported by, geologic evidence accumulated in those fields where oil has been produced. In the search for new fields, the principles evolved, if true, would suggest the procedure which should be followed.

The expression of the old time practical oil man, "Oil is where you find it," still remains the final test. Yet there are degrees of certainty, or uncertainty, in the drilling of oil wells which it is possible for the geologist to point out before money is needlessly wasted in areas that are condemned to failure before drilling is begun. The elements that determine the success or failure of a given test are its structural location and the presence of petroleum in the beds reached by the drill. Definite evidence that either oil or the reservoirs suitable for its accumulation in commercial quantities are lacking would prevent any but the most foolhardy from drilling in such a location. Consideration of the structural evidence has been given an important place in our studies of oil geology. Less time and effort have been devoted to consideration of the probabilities of the existence of the oil itself.

As concentration of oils and gases into commercially workable deposits implies the previous existence of those substances, it would seem advisable to consider the factors determining their existence first.

The first point that arises is that of the existence of conditions suitable for the accumulation of organic materials from which petroleum might have been derived at a given place at some time in the past. Next is the question of the sufficiency of the agencies of alteration to convert this debris into liquid and gaseous hydrocarbons of the petroleum family. Assuming that the area fulfills the conditions postulated, there still remains the question of the present existence of the oil in the strata.

The destruction of petroleum through its decomposition into carbon and hydrogen, its loss through seepages at the surface, and its conversion into asphalt and other solids are reasons for numerous failures in sections where all other factors appear to be most favorable. The finding of asphalt, mineral waxes, asphaltites, or pyrobitumens is considered as a favorable indication of the presence of petroleum; but as these substances are the products of the alteration of petroleum, they are not absolutely certain guides to its presence. The importance of such evidence is sufficient to warrant its careful consideration in a later chapter. Let us take up the more general considerations first.

Igneous Rocks.—Rocks are grouped in three major classes by geologists. These are igneous, sedimentary, and metamorphic. The first group contains all types resulting from the solidification of liquid rock solutions or magmas below the surface and lavas and ejected solids on the surface. If the inorganic theories were correct, such rocks would contain the bulk of the world's petroleum. Instead we note that the presence of commercial quantities of petroleum in rocks of igneous origin is so unusual as to be considered a freak condition. In keeping with their belief in the organic origin of oil, nearly all geologists agree that areas in which igneous rocks are common are areas in which there is the least possibility of the finding of oil.

Care must be exercised that the principle is not applied too rigidly. Those sections in which massive igneous rocks of wholly crystalline character, such as granites, syenites, diorites, and gabbros, are found are not likely to contain oil. These were formed at great depths below the surface under conditions of extreme temperature and pressure. Their downward extent is seldom known and the general feeling is that the chances of finding oil decrease with increasing penetration of such masses. All igneous bodies, however, are not of this type. The wall-like dike and the thin stratum-like sill are usually only partly crystallized. If fully crystallized, the crystallization is abnormal or pegmatitic, making it easy to distinguish them from the massive crystalline types. Such bodies form a very small portion of the area in which they occur.

The possibilities of oil in such areas are determined by the character of the other rocks rather than by the presence of the igneous ones. Basalts and other igneous rocks, resulting from the solidification of lavas, and tuffs, formed by the cementing together of volcanic ashes, cinders, and bombs, are seldom of great thickness. Their existence on the surface, while generally indicative of conditions unsuited to the occurrence of oil below them, does not prove that it cannot be present in the underlying sedimentary beds.

Sedimentary Rocks.—The second of the major series of rocks is the sedimentary group. The unconsolidated sediments from which these were derived were laid down upon the surface by wind, water, or ice. They are in many cases heaped in a disorderly manner and in other instances carefully sorted and laid down like blankets covering hundreds of square miles. All of the world's petroleum is found in intimate association with sedimentary rocks, but not all sedimentary rocks contain oil. The existence of the oil, especially of commercially recoverable amounts, is limited very definitely to a few beds that have been subjected to conditions favorable to the development of oils. The history of a sediment may, if it goes through a complete cycle, be said to contain four stages: deposition, lithification or rock formation, metamorphism or rock alteration, and weathering or rock distintegration. The last is only of indirect interest for the moment as we must look mainly to the unweathered rock for our oil. The processes involved in the other three stages are of major importance.

Glacial Deposits.—The accumulation of organic debris postulates a moderate equable climate. It need not be of tropical nature but must be one in which plant and animal life can flourish. Climatic conditions like those of Greenland, Antarctica or even northern Siberia and Labrador are not likely to permit the development of life to the degree essential to the formation of such accumulations as those from which oil has come. The identification of rocks in any area as the products of the solidification of debris laid down by glaciers is in itself conclusive evidence against the deposition of organic matter convertible into oil at a later date. While oil may have been formed in sediments deposited at an earlier date and have migrated up into those of glacial origin, the possibilities of such occurrence are poor and depend entirely upon the existence of suitable conditions at another time in the earth's history. Where glacial deposits are of great thickness, the outlook must be considered as most discouraging. Fortunately glacial deposits are readily recognized by their bouldery and uneven texture and the lack of true stratification. Organic matter is of minor importance.

Table 29.—Section of Typical Glacial Deposits. Generalized Columnar Section of the Quaternary Deposits in Iowa.*

Subdivision.		Lithologic character.
Recent series.		Chiefly alluvium. Most of the alluvium is doubtless of glacial origin.
Pleistocene series.	Wisconsin drift.	Unweathered calcareous till with sandy and gravelly beds and large amounts of outwash sand and gravel.
	Peorian deposits (loess).	Old soil; much loess.
	Iowan drift.	A thin sheet of light-yellow clayey till, with numerous large granite boulders.
	Sangamon deposits.	Soil and vegetal deposits
	Illinoian drift.	Clayey till, not quite so dense as the Kansan.
	Yarmouth deposits (including Buchanan gravel).	The Buchanan gravel consists of extensive irregular gravel deposits between the Kansan and Iowan drifts.
	Kansan drift.	Tough, hard clayey till, with some sandy beds, especially in upper part.
Aftonian gravel.		Irregular beds of gravel; also old soil and muck.
Nebraskan drift.		Dark plastic till with old soil and beds containing much wood; sand and gravel chiefly underlying till.

* After Meinzer, O. E., Norton, W. H., and others: U. S. G. S. Water Supply Paper 489, p. 291, 1923.

When unconsolidated, glacial debris is called till; when consolidated, the rocks formed are known as tillites. They are heterogeneous mixtures of rock materials varying in size from the finest grains visible under the microscope to blocks of many tons. Associated with material which has been deposited directly by the ice is the partly sorted matter laid down by water arising from the melting of the ice. Such matter generally forms a sandy clay or pellodite having seasonal bands, light for summer and dark for winter. The pellodite particles are distinctly angular and contain feldspar, calcite, and other easily decomposed and dissolved minerals in addition to the normal quartz and kaolin.

Desert Deposits.—Similarly no one questions the improbability of the accumulation of organic debris under desert conditions. The Great Basin between the Rockies and the Sierra Nevadas, the Sahara Desert of North Africa, and the Mongolian Desert of Central Asia contain a minimum of life. Desert deposits differ both in chemical and physical character from those laid down in humid or marine areas. Carbonaceous matter is almost entirely lacking. This is indicated by the absence of dark blues, dark grays, greenish blacks, and distinctly black colorations in the clays. Instead such clays are apt to be of strong red or yellow coloration. The absence of the darker colors lies in the absence of carbon and the presence of ferric compounds of iron.

Ferric iron is a strong coloring agent, producing reds and yellows. When part of the oxygen is removed from ferric compounds by carbonaceous matter, ferrous compounds are formed. These are neutral or dark in color. Probably the neutral carbonate is largely formed. It is somewhat soluble in water. Where the percentage of carbonaceous matter is not sufficient to cause dark coloration, it may serve to neutralize the striking iron coloration and produce white or light grays in the sediments. Where the carbonaceous or organic matter is large in amount, black is the prevailing color.

Neutralization does not necessarily imply the removal of the iron content. Many distinctly black shales, when fired in a brick or pottery kiln, turn red through the burning out of carbonaceous matter and the reoxidation of the ferrous iron to the ferric form. Dark colored sediments, on exposure to weathering, may lose their dark coloring matter and weather red or yellow for the same reason.

Red and yellow colorations, if taken alone, are guides whose value is somewhat questionable. Soils of yellowish or brown color as well as grays and blacks are common in moist temperate zones, and reds and deep brownish reds are common in tropical areas. Such soil colors are due to the oxidation of the original matter of the rocks by aërated surface waters circulating through them. There are other and more satisfactory means of identification of arid and desert conditions.

Desert areas are sections of extremes of temperature. The daily range of temperature may be as much as seventy-five degrees and the yearly range, as high as one hundred and fifty. Rocks in such areas are ruptured and broken down by the stresses caused by alternate periods of expansion and contraction brought on by temperature changes. Rocks break down into mineral fragments, but the minerals are not altered chemically because of the absence of agencies capable of bringing about such alteration. The loose soils resulting from this type of weathering contain quartz, feldspar, calcite, micas, hornblende, pyroxene, and in fact all of the minerals of the rocks from which they were formed.

The absence of sufficient rainfall to form permanent streams limits the removal to short periods following irregularly occurring storms, and to the action of the wind. Accumulations of ''slide rock'' or talus deposits may be anticipated. From the more completely disintegrated rock debris, the wind and water will remove whatever they are capable of handling. In the case of water this means the loose fine grained matter and the soluble products of a limited amount of decomposition. The mineral matter removed in suspension in the water is of the same general nature as that which might be taken up by the water of humid regions. However, the weathering of granite and other feldspathic rocks is normally accompanied by the decomposition of the feldspars into kaolin, quartz, and water soluble compounds. The identification of unaltered feldspar in large amounts in sandstones is considered as fairly conclusive evidence that the feldspathic rock from which it came was broken down under arid or semi-arid conditions. Irregular bedding and wide variation in the size of grains, together with extreme angularity of the grains, are direct indications of close proximity of the place of deposition and the source of the material forming the deposit. Arkose sandstones, possessing a large content of angular, poorly sorted feldspar, are an ideal indication of arid or semi-arid conditions.

The material removed by the wind is naturally of fine grain. Quartz is the predominating mineral found in dune deposits of desert areas, but such sands may contain other products of the disintegration of the parent rock as well. Wind blown quartz sands show the effects of constant abrasion in smallness of size and rounded character of the grains. Feldspar and other softer minerals are largely ground down into finer dust-like grains and carried beyond the confines of the desert area.

According to some, the name "loess" should be applied to deposits of materials high in feldspar and disintegration products other than quartz. Much loess is characterized by such angularity of grain as to suggest that wind action is not the only agency causing its concentration. Because of this other writers consider loess to be the product of glacial grinding and its final concentration to be accomplished by a minimum amount of wind or stream action. In any case the conditions suited to the formation of loess are unsuited to the accumulation of oil forming debris.

Probably the most satisfactory means of the identification of arid climatic conditions in past ages is that of the presence of bedded deposits of chlorides and sulphates of potassium, sodium, magnesium, and calcium. Excepting the sulphate of the last of these, all of the compounds are extremely soluble in water. Calcium sulphate is soluble to the extent of one part to every five hundred of water. The waters of inland drainage basins, such as Great Salt Lake, the Dead Sea, and Lake Urmi, contain large amounts of such salts. The exact proportions of each and of the carbonates that frequently accompany them vary with the character of the rocks leached by the waters of the streams emptying into the final basins. The percentage of salts dissolved in such lake waters may reach as high as 25% of the weight of the water.

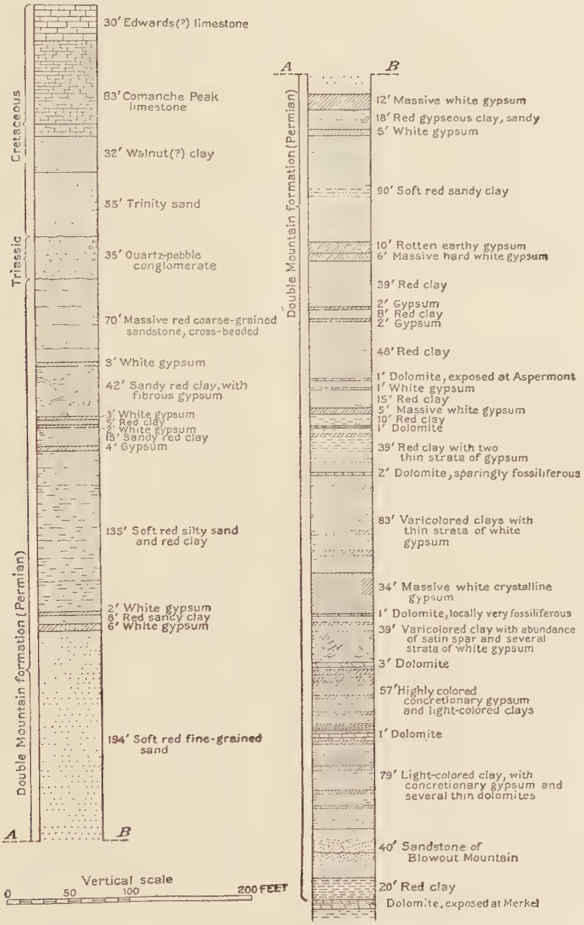

30′ Edwards(?) limestone
83′ Comanche Peak limestone
32′ Walnut(?) clay
55′ Trinity sand
35′ Quartz-pebble conglomerate
70′ Massive red coarse-grained sandstone, cross-bedded
3′ White gypsum
42′ Sandy red clay, with fibrous gypsum
3′ White gypsum
5′ Red clay
2′ White gypsum
15′ Sandy red clay
4′ Gypsum
135′ Soft red silty sand and red clay
2′ White gypsum
8′ Red sandy clay
6′ White gypsum
194′ Soft red fine-grained sand
Cretaceous
Triassic
Double Mountain formation (Permian)
A
B
Vertical scale
0
50
100
200 FEET
A
B
Double Mountain formation (Permian)
12′ Massive white gypsum
18′ Red gypseous clay, sandy
5′ White gypsum
90′ Soft red sandy clay
10′ Rotten earthy gypsum
6′ Massive hard white gypsum
39′ Red clay
2′ Gypsum
8′ Red clay
2′ Gypsum
48′ Red clay
1′ Dolomite, exposed at Aspermont
1′ White gypsum
15′ Red clay
5′ Massive white gypsum
10′ Red clay
1′ Dolomite
39′ Red clay with two thin strata of gypsum
2′ Dolomite, sparingly fossiliferous
83′ Varicolored clays with thin strata of white gypsum
34′ Massive white crystalline gypsum
1′ Dolomite, locally very fossiliferous
39′ Varicolored clay with abundance of satin spar and several strata of white gypsum
3′ Dolomite
57′ Highly colored concretionary gypsum and light-colored clays
1′ Dolomite
79′ Light-colored clay, with concretionary gypsum and several thin dolomites
40′ Sandstone of Blowout Mountain
20′ Red clay
Dolomite, exposed at Merkel

FIG. 6.—Typical Columnar Section of an Area of Red-bed and Salt Deposition. Section showing strata exposed along Double Mountain Fork of Brazos River from Flattop Mountain, Haskell County, to top of Double Mountain, Stonewall County, Texas. After Stone, R. W.: U. S. G. S. Bull. 697, p. 254, 1920.

The waters entering such final basins contain in most cases so little of the salts that they are called fresh waters. The large content in the lakes is a direct indication that evaporation equals the amount of the incoming stream water. Sooner or later the waters of such basinal lakes will become fully saturated and salt deposition begin. The deposition of the least soluble of the major constituents, that is, the calcium sulphate, will normally take place first. Later, if the process is not interrupted, sodium, magnesium, and potassium compounds will be deposited.

The name, Dead Sea, is indicative of the absence of any but the lowest forms of life in the concentrated brines of such basins. For the most part the vegetation in the country around them is stunted and dwarfed and limited to a few favorable localities of small extent.

Cut-off Basin Deposits.—Deposits formed in such basins do not normally reach great thickness and are of different origin and history than those in which the gypsum and salt beds now underlying thousands of square miles were laid down. These larger prehistoric basins were undoubtedly formed during periods of uplift in which the connection between eperic seas (arms of the ocean extending over the low lands of the continents) and the oceans were severed. The severance may have been complete as in the Caspian Sea of today, or only in part, as in the case of the Red Sea. Neither example is a satisfactory one to show the conditions of the past. The connection between the Red Sea and the Gulf of Aden and the open waters of the Indian Ocean is deep enough to permit movement in both directions. Yet the limited number and size of the streams entering the Red Sea and the extremely high rate of evaporation from its surface have increased the salinity of its waters from the 3½% of the ocean to an average of 5½% in the vicinity of the Gulfs of Suez and Sinai. This points to a steady inflow of water from the ocean rather than an outflow.

During the last few years the waters of the Caspian Sea have become fresher. This abnormal and probably temporary condition is due to the steady movement of its waters into a large gulf on its eastern side, known as the Gulf of Karaboghaz. Except that its waters are derived from the Caspian Sea rather than from the ocean and differ therefore from ocean waters in the nature of their salt content, the Gulf of Karaboghaz is probably the closest example we have to the salt deposition basins of the past. Practically no water enters the Gulf except through the narrow and shallow channel which connects it with the Caspian. Because of the extremely high rate of evaporation in the basin, the current always moves into it. The salt content of the waters entering has been placed as high as 350,000 tons daily.

While Caspian water contains only slightly more than 1% of dissolved salts, the water of the Gulf contains up to 28%. Its waters no longer support life, and saline deposits are forming on its bottom. Calcium sulphate is being precipitated continuously along its margin. The deposition of sodium chloride has not yet begun, but the saturation point for sodium sulphate is reached when the waters are chilled in winter and deposits of that salt are formed. Unless the current between the two bodies is reversed, the waters of the Caspian will become practically fresh while the bottom of the Gulf will be covered by a thick bed of salts. After the Gulf has been filled up, the Caspian will again become the final basin and the salt content of its waters slowly rise.

The existence of outcrops of sediments characteristic of cut-off basins is not indicative of the absence of oil and gas in underlying sediments. In fact some of the world's most prolific horizons have been discovered after drilling through hundreds of feet of gypsum, anhydrite, salt, and red sediments usually considered as most unpromising indications. Except where the basins are extremely small in size it is not advisable to infer that the presence of such beds is proof of the absence of favorable conditions for oil formation and accumulation in beds of the same age in other portions of the basin. Exploratory work in the Permian basin of West Texas was postponed for many years because of the belief that the Permian beds contained no oil. This conclusion was reached after examination of Permian outcrops had indicated that even the beds of early Permian age, which outcrop on the eastern edge of the basin, were containers of large amounts of gypsum, anhydrite, and salts. It was assumed that the horizons would have much the same character to the west, where they dipped far below the surface. The probability of the existence of oil in the underlying Pennsylvanian beds was admitted, but their depth was considered as prohibitive. The drill has demonstrated that the shallowing of the sea in this area was a progressive phenomenon, and, that, while salt deposition was characteristic of the early Permian in the eastern portion of basin, open water conditions prevailed in the central and western portions until much later in the period. These areas are now producing on a large scale from Permian horizons.

Sediments of Humid Areas.—The greater part of the sedimentary formations were not laid down under such distinctly unfavorable conditions as those of glacial periods or of extreme aridity. The absence of conditions favorable to the existence of life in some form can hardly be implied where deposits were laid down in marine waters or upon land surfaces enjoying humid climatic conditions. In such, the questions arising are those concerning the nature of the life, its abundance, and the chances of its preservation.

The normal continent contains mountains or elevated areas from which its principal streams flow toward the oceans. The power of such streams to erode the surface in their upper courses is considerably greater than it is when they flow out upon the coastal and interior plains. In fact such streams are frequently unable to carry the load of eroded material which they have taken up as far as their mouths. Deposition in the piedmont or transition belt between the mountains and the plains is common. The material deposited differs from the playa deposit of the desert section in that it contains practically no soluble salts, the carrying power of water for such matter being independent of its velocity. Sands and clays in heterogeneous heaped deposits of great extent may result. Such deposits are prominent along the eastern front of the Rockies, the southern slope of the Himalayas in India, the eastern flank of the Andes in Brazil and Argentina, and other similar areas. Marked cross-bedding is an indication of the rapidity and the irregular manner of their deposition. Frequent angularity of grain indicates that the debris was not carried great distances. While the organic matter deposited with the rock debris naturally varies considerably with different places, appreciable amounts were probably always deposited even under the least favorable of humid climates.

On the other hand, the preservation of such matter is difficult. Between periods of deposition, which from the nature of the method must be intermittent, decomposition of the organic matter must be rapid. The debris in such areas is largely exposed to the attack of aerobic bacteria. Even if slightly covered, its decay is encouraged by the constant and largely unrestricted movement of soil waters carrying decomposing organic acids, dissolved oxygen, carbon dioxide, and other active agents. Such deposits may, before the end of the period of soil water action, lose all of their organic matter and have their iron content so oxidized that it shows the red coloration usually considered as indicative of deposition under arid conditions.

River sand bars and mud flats are closely related to the true piedmont deposit. The first result from slight irregularities in slope of the stream or differences in the carrying power of the water at different stages. Mud flats are largely due to the overflowing of river banks and the spreading of the water upon low lying flat lands. While sorting and grading is carried to a much higher degree than in the piedmont section and grains are much more rounded and of smaller size, river bars show marked evidence of cross-bedding. They and the river flat deposits, unless continuously covered by swamp waters, are subject to rapid aerial decay in the same way as the piedmont deposits are.

Where the swamp condition exists, the organic matter brought in during the period of river overflow may be preserved indefinitely from complete decay. Probably it will be minor in amount to that growing there and deposited in situ. The swamp is always an indication of imperfect drainage. This may be brought about by surface agencies or by crustal movements. The ultimate end of all lakes in humid regions is conversion into swamps as their bottoms are filled with sediments and the barriers behind which their waters are imprisoned are worn away. Finally the swamp may disappear. Lake deposits, unless the lake is of large enough size to permit reworking of the sediments by wave action, are similar to those of the piedmont area. Deposits of large lakes may resemble those of the ocean. Bedding is likely to be well developed in such cases and sorting according to the size of the grain is commonly in evidence. Organic debris, either of the lower types deposited in situ or carried in by water or wind, has an excellent chance of preservation. With the development of swamp conditions, accompanied by stagnancy of waters, peat formation is likely to occur over much of the area of former lakes.

Lakes and the swamps derived from them are strictly temporary phenomena. Unless crustal movements bring abnormal conditions after the lake has been formed, the destruction of the barrier takes place simultaneously with the filling of the basin behind the barrier. With the destruction of the barrier, normal erosion will rapidly disintegrate and remove the material that has been deposited. Because of this, lake and lake-swamp deposits and, in fact, all types of deposits laid down in areas elevated above the sea level are less commonly preserved through geologic time than those of marine or nearly sea level origin.

Furthermore, it should be noted that the thickness of the beds containing organic matter is distinctly limited by the depth of the original basin. Subsidence of the area, unless accompanied by pronounced warping of the crust, will not make possible the continuance of the conditions essential to the accumulation of coal and oil source materials, or the repetition of these conditions. Yet these conditions are indicated by the geologic sections of areas in which coal and oil occur today.

Coastal Swamps.—Swamps in upland areas are not the only types. Those which lie almost, if not actually, at sea level are of greater importance both today and in past geologic time. The Great Dismal Swamp of Virginia and North Carolina, the Everglades in Florida, and the wide swamp areas of the lower Mississippi, Amazon, and Ganges Rivers are but a few of the numerous examples of such areas now in existence. Such swamps may be considered as having been formed by crustal movements bringing an almost level area to sea level or to a level so close to the absolute sea level that water circulation is practically stopped. This may be accomplished either through uplift or submergence. While probably not the main factor in the development of extensive areas of this sort, river waters and ocean waves play an important part as contributing factors.

Where the exchange of water between the low lying areas and the ocean continues, the water in them remains salty and the life is largely of marine types. Where the sea water is excluded either because the swamp level is slightly above the high tide level or because of the barrier to exchange formed by a thick growth of vegetable matter, the water will contain non-marine types of life.

Swamps of this type possess all of the conditions fundamental to the accumulation and preservation of organic debris on a large scale. Rapid elevation or submergence will halt accumulation. In the case of uplift it may cause the weathering away of the deposits formed. Rapid movements are less common than those of a gradual oscillating nature. They may make it possible for a period of much the same conditions to continue for thousands of years and, if interrupted, to be resumed many times in the same place. Such conditions are ideal for the preservation of vegetable matter in its entirety and the formation of peat which may later develop into coal. The cellulosic matter in such areas is so important as completely to overshadow the relatively small percentage of material which contains little or no oxygen. Accumulation is so rapid that the anerobic bacteria are unable to alter materially the ratio of carbohydrate to hydrocarbon before burial ends the biochemical stage. Only in the deeper sections in which the higher forms of life do not flourish does the carbohydrate seem to be of less importance than the material of a sapropelic or hydrocarbon nature.

Deep Sea Deposits.—Before discussing the deposits of the strand line, which would logically follow, let us consider those of the deep sea areas. The waters of the ocean basins have a temperature of 34° to 35° F. or slightly above the freezing point. They are practically devoid of light and movement. Life is largely restricted to the waters close to the surface and consists of minute organisms having calcareous or siliceous shells. These, together with volcanic dust and cosmic particles, form the fine soft deposits called oozes, which cover the bottom of the ocean basins proper. The possibility of the preservation of oil forming materials in such deposits is purely an academic question. Shells of some diatoms and foraminifera have been identified in deep sea oozes; but, as sedimentary rocks found upon the surface of the continents do not contain types similar to them and are different in other respects, the conclusion that such deposits have not contributed to the oil deposits of the world seems justified.

Between the hundred-fathom line and the deep sea proper is an area in which the deposits partake of a two-fold character, being partly of continental and partly of deep sea nature. The material of continental derivation is extremely fine and accumulates as fine muds of different colors. Glaüconite, a green-colored deposit, seems to be common in the areas between the shallow waters of the continents and the deeper waters of this intermediate area. The fine muds of the intermediate slopes are, like those of the deeper basin areas, considered to be of little interest to the petroleum geologist.

Near Shore Sediments.—On the other hand the deposits of the strand line, the epicontinental shelf, and the epeiric sea, are the common associates and containers of oil. These consist almost entirely of clays and derived shales, the calcium carbonate rocks (chalk and limestone), and sand deposits of varying porosity, size of grain, and degree of cementation. Cross-bedding is prominent in river delta deposits and some of the sand bars, but gives way to parallel-bedding in the deposits laid down a short distance from the shore. The deposition of silts, muds, and sands is accomplished largely by physical means, the carrying power of the water being materially decreased as it emerges from the mouths of streams and mingles with the comparatively quiet water of the ocean or of its larger arms.

TABLE 30.—FORMATIONS IN A TYPICAL TERTIARY OIL PRODUCING AREA. Representative Formations in the Dutch East Indies Oil Fields.*

	Sumatra Palembang.	Sumatra Djambi.	Borneo.
(1) Upper Pliocene.	Deeply coloured mottled unctuous clays. Sometimes with brown coal. Tuffs and Pumicestone series (Upper Palembang).	Azure blue weathering to yellow unctuous tuffs sharply defined from Middle Palembang (Upper Palembang).	Similar to that of Djambi.
(2) Lower Miocene.	Soft brown clay beds with many coal-seams (Middle Palembang).	A sandy shale without marine fossils. In south-east Djambi there are a few brown coal beds.	Limestones without fossils, mottled clays and friable sandstone without fossils. Brown coal beds.
(3) Upper Miocene.	Molasse sandstone without fossils, clays with sandy joint faces (Lower Palembang)	True marine beds, greenish-blue clays and sandstones. Fossils in all beds except sandy shales. Glauconite limestone. Tuff sediments occur as in Palembang in several places.	Sandy clays and sandstones often with many fossils. Grey limestone without fossils. Brown coal beds.
(4) Lower Miocene.	Goemai beds. The highest of the marl series is black clays and breccias (1,500 m. thick). The lowest is a gravel division of 1,500 m. thick, and brown marly shales and limestones without fossils.	Telisa beds. Chocolate brown and hard grey shales and concretionary clays. Limestone concretions and even beds. Plant remains numerous Marine fossils.	Clays and all limestones without fossils. Three oil horizons in Sanga-Sanga.
(5) Oligocene.	Brown marly clay with cylinders of lime concretions (Septaria), orbitoids and corals. Blue and greenish marine sediments. Oil horizon in the Goemai Mountains.	Slates and orbitoidal limestones, with corals and gastropods.	Limestone with fossils, caves and salt springs. Hard well-bedded knobly slates. Nummulites and orbitoids. Aquitane and Burdigal beds, limestone with fossils and some marine sediments.
(6) Eocene.	Quartz sandstone, coals.	Quartz sandstone and quartz conglomerates	Quartz sandstone and quartz conglomerates, badly represented. Verbeek gives this as the real *Nummulite* horizon near Matapœra, South Borneo.

* After Thompson, A. B.: Oilfield Exploration and Development, Vol. 1, p. 485, 1925.

The salts present in that water undoubtedly assist materially in hastening deposition. Normally, limestones and chalks result from the action of lime secreting animals upon the soluble calcium bicarbonate dissolved in sea water. This is converted to the insoluble carbonate. Some calcium carbonate is deposited as a straight chemical precipitate from a saturated solution in the same manner as salt is in closed basins. The amounts deposited in Pre-Paleozoic periods in this way are believed by some geologists to have been large. The amounts so deposited in recent times or during the periods when oil-yielding rocks were deposited were probably insignificant compared with those precipitated by organic life.

Some limestone is of detrital origin; that is, deposited as grains or fragments from suspension in the same manner as ordinary sand or salt. This type of deposit owes its existence to extremely rapid disintegration of limestones, the streams carrying away calcite material both as dissolved and as suspended matter. Through solution and recrystallization such limestones may take on a massive character and conceal the manner of their deposition. Similarly, while shales are considered as being composed largely of detrital material, beds of diatomaceous shale are composed mainly of the hard siliceous skeletons of microscopic plants called diatoms.

While sandstones and porous limestones are the normal containers of oil, the close proximity of black shales, clays, or marls is considered as indicating that such beds were more probably the source of the oils. In support of this view there are three lines of proof: first, the relationship between prominent black or dark brown carbonaceous shales and the world's prominent oil producing horizons; second, the analyses of such shales both from the chemical and microscopic standpoints; and thirdly, the differences in the conditions essential to the deposition of the several types of sediments.

The only shales present in oil producing areas which have been analyzed to any great extent are the Devonian black shales of Indiana and Kentucky and the Monterey shales of California. In these the organic matter still remaining is sufficient to indicate that they may be used as a source of shale oil in the future. Both contain fossil remains—the Monterey, diatom remains; and the Devonian, a prolific fauna containing numerous species of both plant and animal nature. Sandstones are comparatively poor in fossil evidence. Dark colors that characterize all clays of high content of organic matter are singularly lacking in sandstones. Except in the case of such beds as the Athabasca tar sands, organic matter is of minor amount. The organic matter in such cases appears to be purely of later introduction. Limestones are composed mainly of animal remains, yet the amount of bituminous or carbonaceous matter which they contain is negligible in comparison with the amount present in black shales.

The great thickness of many limestones makes the total of their organic matter large. They cannot be dismissed entirely as containers of the original matter from which petroleum has been derived. The bituminous matter of many limestones may be considered as of secondary introduction, but the dark coloration of other massive limestones leads to the conclusion that carbonaceous matter was preserved along with the calcareous matter at the time of deposition.

The prominence of the Devonian black shales in the eastern and central parts of the United States and of the Monterey shales in the producing areas of California has been mentioned. The black Smithwick and Lower Bend shales are prominent in North Central Texas, the Cherokee shales in the producing horizons of Pennsylvanian age

TABLE 31.—SECTION OF FORMATIONS IN A TYPICAL OIL PRODUCING AREA OF PALEOZOIC AGE. Rock Formations in the Ranger District of the Bend Arch.*

System or series.	Group or formation.			Character.
Lower Cretaceous 0–50 feet.	Trinity sand, 0–50 feet.			Coarse conglomerate, sandstone, and sand.
	Unconformity			
Pennsylvanian, 4 200+feet.	Cisco group, 500 feet, exposed.			Gray and blue clay and shale, brown and gray cross-bedded sandstone, and blue to gray thin-bedded fossiliferous limestone.
	Canyon group, 800–1,000 feet.			Gray multiple-bedded and yellow thin-bedded fossiliferous limestone, brown cross-bedded ferruginous and gray even-bedded calcareous sandstone, and gray and blue shale and clay.
	Strawn formation, 1,750–2,000 feet.			Fine-grained thin-bedded and coarse-grained heavy-bedded gray sandstone, blue and black shale, and siliceous thin-bedded limestone.
	Unconformity			
	"Bend series," 1.000–1 280 feet.	Smithwick shale, 230–330 feet.		Black shale and black thick-bedded limestone.
		Marble Falls limestone, 600–650 feet.		Black shale, black and gray limestone, and gray lenticular sandstone.
Mississippian, 150± feet.		"Lower Bend" limestone.	150± feet.	Black limestone.
		"Lower Bend" shale.		Black shale.
	Unconformity			
Ordovician and Cambrian, 545+ feet.	Ellenburger limestone, 545+ feet			White dolomite, crystalline limestone and sandstone.

* After Reeves, Frank: U. S. G. S. Bull. 736, p. 144, 1922.

in Oklahoma and Kansas, the Benton shales in Wyoming, and the San Felipe shales in the Tampico-Tuxpam area of Mexico. Numerous other occurrences of shale formations in close proximity to, or actually containing, the oil-yielding sands and porous limestones, might be mentioned. Failures to find oil and gas in porous limestones and sandstones, which differ in no way from those containing oil and gas except in the lack of association with dark colored shales, are too frequent to pass unnoticed. From this alone the position of the dark carbonaceous shale as the source of the major part of the world's petroleum seems to be fully established. The light colored shale in which the content of organic matter is low does not apparently contribute to the supply of oil.

Normally sands are laid down in shallow water and closer to the shore than either clays or lime deposits. Delta deposits and sand bars in which sandy material is most prominent are largely formed between the level of high and low tides. Slight uplifts bring them above the level of the sea. During periods when such sands are above sea level, they are exposed to the solvent action of ground waters and to aerial decay. The completeness of the decay is largely due to the porous nature of the sands themselves.

Reasons for the limited percentage of carbonaceous matter in limestones are less evident. If the organic matter contained in the fleshy parts of the original shell organisms was preserved, the organic matter in limes should be materially greater than that in the shales. Calcareous life flourishes only in clear waters, usually at some distance from land. While a considerable part of lime deposits consists of the shells of sea animals which inhabit the bottom, the greater part is made up of the remains of free floating and swimming organisms which live in the upper layers of the water. The downward movement of the shell remains is slow, and considerable of the lime may be redissolved before it reaches the bottom. Calcareous matter is generally absent in deep sea oozes despite the prevalence of lime secreting organisms in the upper waters of those seas. Similarly it appears probable that the carbonaceous matter present in calcareous and siliceous organisms inhabiting all but the most shallow portions of the sea is largely redissolved or decomposed before reaching the bottom.

The Deposition of Organic Debris.--Neither quartz sands nor lime particles are capable of attaching oily and fatty particles to themselves to the extent that clay particles are. In waters containing considerable amounts of finely divided organic matter and mud particles having this property, the joining of organic and inorganic matter and their precipitation together may be expected. The deposition of organic matter would be materially hastened and the chance of its preservation greatly increased. Continuance of the same type of action would provide a clay covering which would terminate the period of biochemical alteration and decomposition. The impervious nature of clays would serve to prevent circulation of ground waters during slight uplifts. Of course, not all silts would cause precipitation or deposition of the suspended matter to the same extent. Coarse silts, because of the weight of the individual particles, would be the best precipitating agents. Silts that remain in suspension for indefinite periods and ultimately form fine deposits, such as those of the deep seas, would be of no value, as decomposition would destroy the organic matter which had attached itself to the particles before deposition took place. The condition of the water itself is important. Unlike sand grains, which are carried in true suspension and maintained in suspension purely by the motion of the water, clay particles are largely in colloidal suspension or solution. The river water on entering a large standing body of water loses its clay content much more rapidly if the latter contains salts in solution. Rapid, close-to-the-shore deposition of clays is more pronounced in ocean waters than it is in the fresh waters of lakes.

Wave action may be sufficient to carry fairly coarse silt for long distances from the shore and break up deposits formed close to river mouths as soon as they are formed. This is logical where the water empties directly into the ocean and not into a partly land-locked basin such as the Mediterranean Sea, the Gulf of Mexico, Lake Maracaibo, and the Gulf of Lower California. While some reworking of silts is desirable in the deposition of oil source materials, the carrying of such material for great distances is unfavorable to the preservation of the organic matter.

Although it is generally agreed that salt water is an important agency in regulating the manner of deposition of oil-forming debris and assists materially in hastening deposition, there is no reason to believe that organic matter will not be preserved in the comparatively fresh waters of land-locked bodies in humid regions. In fact, the protection against washing by strong ocean currents afforded by the topography, together with the abundance of organic matter, should make such areas the most logical place for the accumulation of black clays and shales. M. A. Goldman[1] calls attention to the high organic content of the clays being formed on the bottom of protected parts of Chesapeake Bay. Conditions existing in the basin of Lake Maracaibo, an arm of the Caribbean Sea, appear to be even more favorable to the accumulation of oil-forming debris than those of Chesapeake Bay. Similar conditions are found in various parts of the East Indies.

The general absence of examples, to which one might point and say, "there is an example of the accumulation of oil source materials," is to be expected. At present the continents are largely in emergence. Epeiric seas, such as those which formerly extended across North America from the Gulf of Mexico to the Arctic, and over Asia to connect the Arctic with the Indian Ocean are unknown. Remnants and reminders of their former extent are present in such waters as the Gulf of St. Lawrence, Hudson Bay, the Gulf of Lower California, and the Baltic Sea. All of these lack one or more of the climatic conditions necessary to the formation of oil-yielding clays and muds.

---

[1] Amer. Assoc. Pet. Geol. Bull., Vol. 8, pp. 195–201, 1924.

The average depth of the epeiric sea was not great. Interbedding of cross-bedded sandstones of delta origin and massive limestones laid down in moderately deep clear waters indicates the oscillating nature of the shore line. Whereas peat formation was characteristic of those periods during which the surface of the epeiric basins was slightly above the level of the sea, the conditions most favorable for the accumulation of black shales and clays were those when they were slightly below that level. The long continued period of deposition was no less essential to the formation of the clay than to the accumulation of peat.

While the tangled mass of twigs, branches, roots, and tree trunks served to retard water circulation and prevent washing away of coal-forming debris, the organic silts were protected from removal only by the land barriers that surrounded the basins in which they were deposited. Land-locking must be considered as of prime importance in the deposition of oil source materials.

The Functions of Metamorphic Agencies.—Before applying the principles just outlined to the distribution of oil horizons among the sedimentary formations of the earth, it is desirable to point out again that organic sediments undergo considerable change before the stage of oil formation and expulsion is reached. Furthermore the oil and the surrounding sediments are subject to alteration that may increase the value of the oil or destroy it entirely. The product of the covering of organic clays is the substance we have called sapropelic clay. Time will cause it to shrink and compact; but, other than reducing its content of water, will not cause material change in the clay. The creation and expulsion of oil into more porous rocks can be accomplished only where the more active agencies of heat and pressure are permitted to function. Static pressure supplied by the deposition of later sediments may be considered as the most important agency in lithification and dehydration. The conversion of organic matter into liquid and gaseous petroleum compounds must be attributed in part at least to dynamic pressure. Without overburden to supply a restraining pressure, dynamic pressure would result in change in physical form rather than in chemical character.

Kerogen shales, such as those of the Rocky Mountain Green River formation of Eocene age, may be considered as not having been subjected to sufficient pressure to convert their kerogen into petroleum. The substantial percentage of kerogenetic matter still present in the

Devonian black shales of the Mississippi and Ohio Valleys and in the Carboniferous shales of Scotland is less easily explained. They differ from the Eocene shales sufficiently in physical properties to indicate that they have had a different history. The areas in which the Devonian shales have been studied the most, namely Indiana and Kentucky, are also the areas in which they have been subjected to the least dynamic pressure and probably covered by a smaller thickness of later sediments than in adjacent areas. It is possible that these shales, despite their age, have not been subjected to static and dynamic pressure much greater than those of the Green River group.

The writer considers that the lower average yield, the difference in character of oil obtained by retorting, and the greater degree of alteration shown by the older shales, indicate that the complete conversion of kerogen is not accomplished until the metamorphism of the shale is well under way. Certainly there is ample evidence to indicate that the Devonian shales were the original source of the oils which are found in horizons above and below them in areas close to those where they have been studied.

Metamorphosed Rocks as Sources of Oil.—In one sense all of the stages through which sediments pass after they have been deposited are stages in metamorphism. Thus lithification and dehydration may be considered as preliminary stages of metamorphism. Ultimately the sedimentary rock loses its original characteristics under the influence of extreme dynamic and static pressure or the heat and gases and liquids associated with intruding igneous masses. When that stage is reached, the rock is no longer called a sedimentary one but is classed as a metamorphic type. In such alteration shales become slates; limestones are converted into marbles; pure sandstones become quartzites; and impure shales and sandstones are altered to schists and gneisses. The outstanding characteristics of such rocks are their crystalline character and the absence of pore space. Bedding planes disappear and are replaced by slaty and schistose structures and cleavages, the perfection of which depends upon the completeness of the metamorphism and the nature of the minerals composing the product. Metamorphism may also, if the proper minerals are present in the original sediments, result in the formation of single complex compounds and the freeing of carbon dioxide, water, or both.

The conditions that not infrequently cause the union of calcite, kaolin, and quartz to produce the complex garnet are conditions that are unsuited to the preservation of the unstable hydrocarbon molecule.

In fact, even if it were possible to prevent its destruction, there would be practically no pore space in which to store it after the conversion of the sediments into metamorphic rocks. The only evidence of the former existence of bituminous matter in metamorphic rocks of sedimentary origin is that indicated by the presence of flakes and specks of crystalline graphite. Metamorphic rocks may also be formed by the dynamic alteration of igneous rocks. These do not even show such evidence.

Regardless of the origin, such rocks must be considered as distinctly unfavorable to the accumulation of oil. Local or contact metamorphism associated with igneous sills or dikes may be of little importance; but where massive bodies of crystalline rocks resulting from regional alteration are found, the possibilities of finding oil below them are extremely small.

Unhappily the stages of alteration of organic remains do not coincide with those of the purely inorganic material. In fact, metamorphism, as the term is generally used, can hardly be said to have begun in sedimentary rocks in which dry gases, the end products of the alteration of oils, are the only substances of the petroleum family remaining.

Between the comparatively young rock, which is just passing through the stage of lithification, and the one which lies on the border line between the metamorphic and sedimentary classes, there are recognizable distinctions. Between intermediate types these distinctions are not so clear. To some extent the pore space of sandstones may be used to indicate the stage in the preliminary alteration to which it has been subjected. Sandstones in the least altered areas are more porous and open than those in areas where alteration has progressed farther. However, porosity is also a function of the size of the grain, the shape of the grain, and of the amount of cement that has been introduced. Similarly, while clays and limestones show differences in different stages, the differences are not such as permit them to be used as indicators of the degree of alteration of petroleum except in a most general manner.

The dynamic agencies that cause the alteration of oils are also active in causing alteration in other types of organic deposits. This means particularly the alteration of coals. The alteration of coal shales or ''slates'' and spent kerogen shales, from which the oil has been formed, should show similar changes; but there are not sufficient

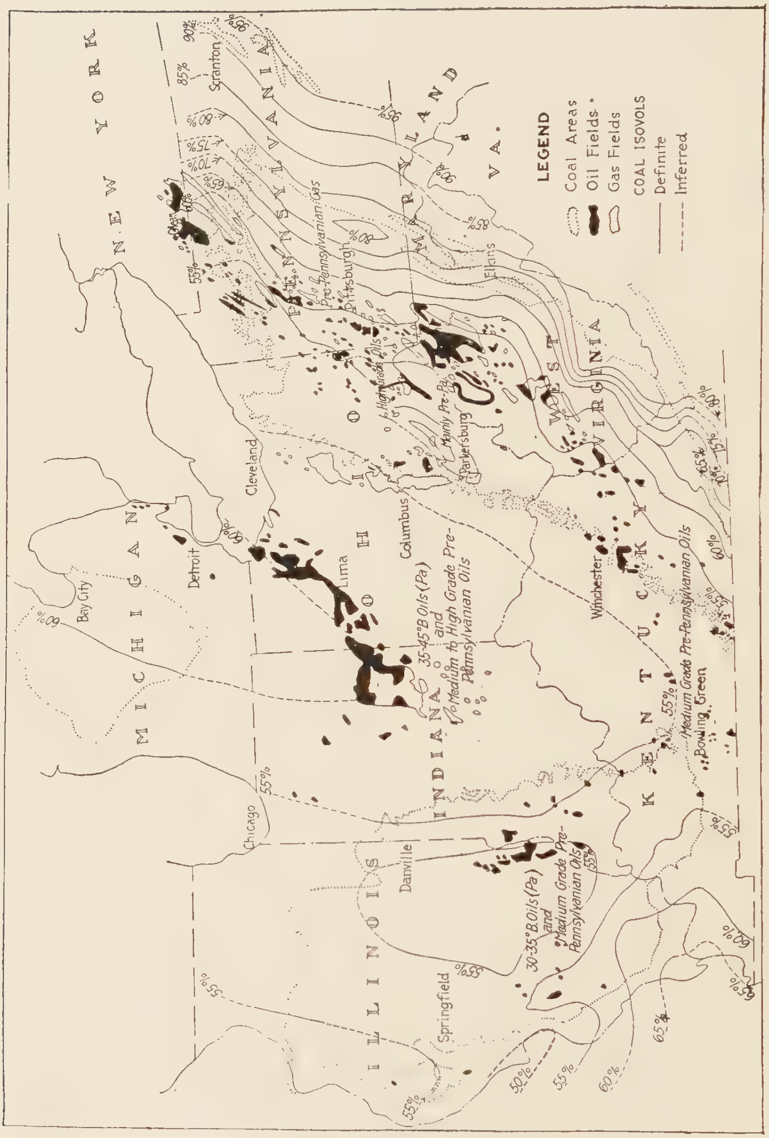


FIG. 7.—Relation of Coal Isovols to Oil and Gas Production in the Eastern Province. After Lilley, E. R.: E. & M. J.-P., Vol. 117, p. 1010, 1924.

data on hand to indicate how changes in their character should be interpreted.

Comparative Alteration of Coal and Petroleum.—The parallelism in location between coals and oils of Pennsylvanian age in the Eastern and Mid-Continent areas of the United States has made it possible to acquire a fair idea of the comparative effects of dynamic metamorphism upon coals and oils. To quote directly from David White,[1] whose studies have been the basis of all later work:

> "7. In regions where the progressive devolitilization of the organic deposits in any formation has passed a certain point marked in most provinces by 65 to 70% of fixed carbon (pure coal basis) in the associated or overlying coals, commercial oil pools are not present in that or other formations normally underlying it though commercial gas pools may occur in a border zone of higher carbonization. The approximate carbonization limits of the rocks containing or overlying oil pools may be found to vary somewhat in different provinces according to the characters of the original organic debris, the circumstances attending its deposition and the geologic structure.
>
> "8. Wherever the regional alteration of the carbonaceous residues passes the point marked by 65 or perhaps 70% of fixed carbon in the pure coal, the light distillates appear in general to be gases at rock temperatures. Occluded oils may in some cases, have escaped volatilization."

M. L. Fuller[2] in applying the principles of White to possible extensions of oil producing areas in North Texas suggests the following relationship:

Carbon ratio over 70%—No oil or gas, with rare exceptions.
65–70%—Usually only "shows" or small pockets. No commercial production.
60–65%—Commercial pools rare but oil exceptionally high grade when found. Gas wells common, but usually isolated rather than in pools.
55–60%—Principal fields of light oils and gas of Appalachian and Mid-Continent Fields.
50–55%—Principal fields of medium oils of Ohio, Indiana, and Mid-Continent.
under 50%—Fields of heavy Coastal Plain oils and of unconsolidated Tertiary and other formations.

The dead lines set by Fuller seem to the writer to be a little low if the coal and the oil are of the same geologic age. The greater part

---

[1] Wash. Acad. Sci. Journ., Vol. 5, p. 212, 1915.

[2] Econ. Geol., Vol. 14, p. 538, 1919.

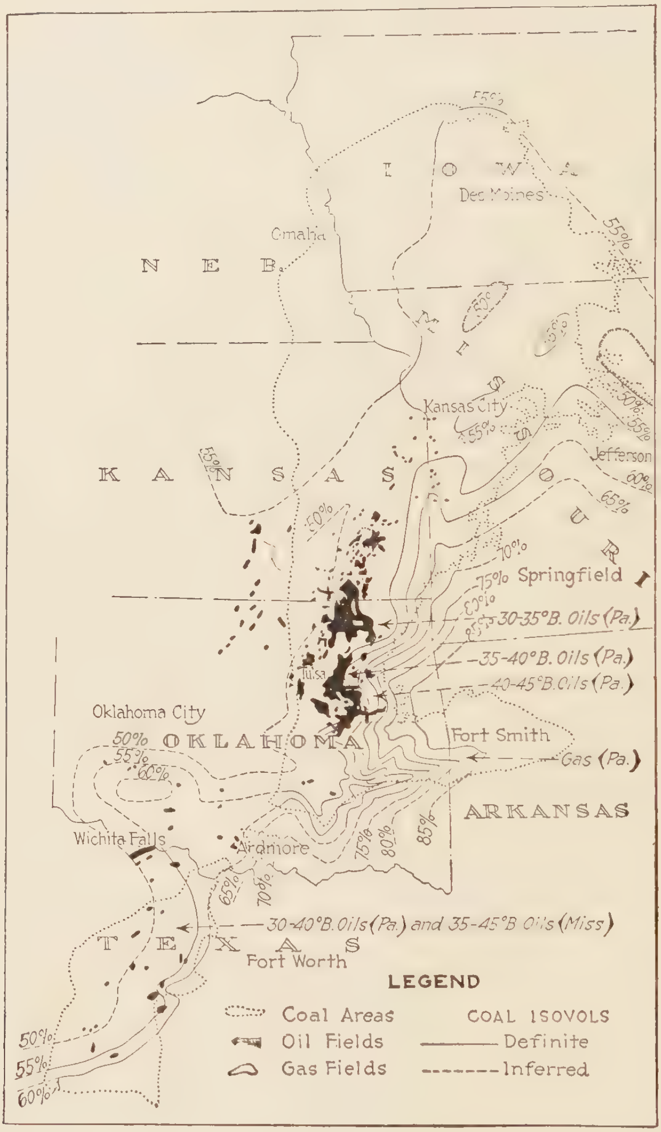


FIG. 8.—Relation of Coal Isovols to Oil and Gas Production in the Eastern Portion of the Mid-Continent Province. After Lilley, E. R.: E. & M. J.-P., Vol. 117, p. 1012, 1924.

of the oil of Pennsylvania is produced from pools lying between the isovols (lines of equal carbon ratio) of 55 and 60%, but the oil is of greater age than the coal beds used as a basis of comparison. Gas is produced in eastern Oklahoma and western Kansas where the carbon content of the pure coal reaches nearly 80%. Substantial oil pools of Pennsylvanian age are found in Oklahoma adjacent to coals having a carbon ratio of 65%. If the relationship be definitely understood to be limited to comparisons between coals and oils of the same age, the author[1] finds that the following relations seem to hold:

Fixed Carbon Percentage	Character of Hydrocarbons
80–100%	No hydrocarbons.
70– 80%	Dry gases only.
60– 70%	Paraffin base oils above 40° B.
55– 60%	Mixed base oils of 35–40° B.
50– 55%	Mixed base oils below 35° B.
Below 50%	Asphaltic oils.

In applying the theory to the possibilities of the existence of oils in formations of different age than those containing the coal, allowance must be made for the greater degrees of alteration possible in underlying beds. When there is no marked unconformity between rocks of successive periods, it is probable that the lowering of the limits set by 5% will cover the conditions adequately. However, where several geologic periods separate the coal horizon from the one in which oil is anticipated, the quality of the oil and the limitations to its existence may bear no relation to the carbon ratios in the younger coals. Marked unconformities, especially those which separate rocks of one geologic era from those of another, would probably show similar lack of relationship between rocks of successive formations.

The relations suggested between characteristics of coals and oils are based upon comparisons between normal samples of each. Ash and moisture do not enter into the carbon ratios used. During all but the last stages of their alteration, cannels and boghead cannels contain abnormally large amounts of volatile matter and correspondingly low percentages in fixed carbon. Sulphur, nitrogen, and oxygen compounds materially increase the density of oils. The character of the reservoir rock containing the oil may influence the density and character to some extent. The resistance of limestones and well cemented sandstones to the mashing and shearing action of dynamic forces is materially greater than that of poorly cemented sands. The carbon

[1] The Oil Industry, p. 30, 1925.

ratios in faulted areas and folded sections where the stresses have resulted in movements of large masses rather than intergranular adjustments are materially lower than in sections where such adjustments have been the sole means of absorbing stresses. Underground waters and gases have in many cases materially increased the density of oils by the addition of new elements and polymerization of the hydrocarbons.

The application of changes in coals to the determination of the exact character of oils is difficult at best. It can only be approximate. Yet use of the theory in delimiting the areas of least probable production and therefore greatest risk to the operator is highly advisable.

Summary.—The organic nature of oil source materials limits the occurrence of oil to those sections in which the conditions suited to the existence of life have been present. While oil is a liquid and thus has considerable freedom of movement, the most likely places in the stratigraphic column for it to occur are those nearest the source beds. Rocks of crystalline character, whether of igneous or metamorphic origin, are not promising indications. The possibilities of sedimentary rocks can be determined in the absence of surface indications of oil by those characteristics which indicate the conditions of their formation. The occurrence of black shales is to be considered as a most promising indication. However, alteration may cause the destruction of hydrocarbons. Where coals are available, they may be used in determining the approximate degree of that alteration.

A SELECTED BIBLIOGRAPHY ON PHYSICAL GEOLOGY.

1. Chamberlin, T. C., and Salisbury, R. D., Geology, Vol. 1, Processes.
2. Chamberlin, T. C., and Salisbury, R. D., Introductory Geology.
3. Clarke, F. W., Data of Geochemistry, U. S. G. S. Bull. 770.
4. Grabau, A. W., Principles of Stratigraphy.
5. Grabau, A. W., Textbook of Geology, Part 1, General Geology.
6. Johnson, D. W., Shore Processes and Shoreline Development.
7. Leith, C. K., and Mead, W. J., Metamorphic Geology.
8. Miller, W. J., Physical Geology.
9. Pirsson, L. V., and Schuchert, Charles, Textbook of Geology, Part 1, Physical Geology.
10. Twenhofel, W. H., Treatise on Sedimentation.

CHAPTER VI.

GEOLOGIC HISTORY AND THE OCCURRENCE OF OIL.

The relative scarcity of petroleum in rocks of some ages, its entire absence in others, and its abundance in a few, indicate differences in the conditions existing in different periods of fundamental importance to petroleum geologists.

Pre-Cambrian Rocks.—The earliest rocks of which we have any direct knowledge are those of Archeozoic and Proterozoic ages. These in North America form the Great Shield of Canada and the cores of mountainous areas scattered throughout the continent. Many of the rocks of this age now showing on the surface are granitic and volcanic in nature. Shales, sandstones, and conglomerates were deposited in much the same manner as they are today. While the fossil record of these ages is scant and may be said to be entirely lacking in the Archeozoic, there is reason to believe that primitive forms of life, such as algae, existed in the Archeozoic, and that primitive marine invertebrates were developed during the Proterozoic. Limestones were

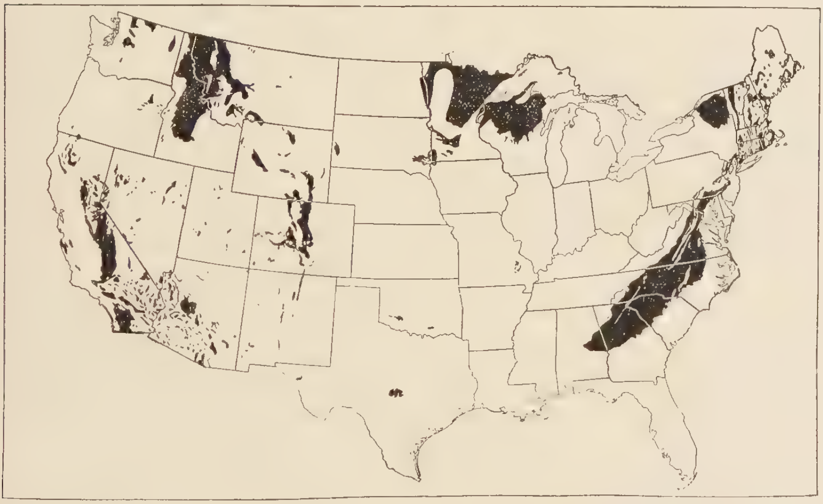


FIG. 9.—Map of the United States showing areas in which Pre-Cambrian rocks or Post-Cambrian intrusive or plutonic rocks are at or near the surface. After Meinzer, O. E.: U. S. G. S. Water Supply Paper 489, p. 198, 1923.

formed in both ages but may have been of chemical and detrital origin rather than organic precipitates. The Grenville series of the Adirondacks and eastern Canada, which is of Archeozoic age, contains an extremely large quantity of graphite. This graphite occurs in quartzite-schists, which may be considered as the products of the alteration of carbonaceous or bituminous sandstones and shales. Their carbon was probably contained in primitive marine plants and animals.

While the life of these eras was entirely different from that of succeeding ages, it certainly cannot be said to have been non-existent. It may, as the existence of disseminated graphite in crystalline quartzite-schists indicates, have been converted into petroleum. Except from the academic point of view, the existence or non-existence of petroleum is of no importance as all known Archeozoic and Proterozoic rocks are so highly metamorphosed as to preclude the possibility of their containing any liquid or gaseous hydrocarbons.

The Cambrian Period.—Broad generalizations cannot be drawn on the periods succeeding the Proterozoic. Rocks of all of them produce oil or gas in some amount. Some yield considerably more than others. In those which produce relatively small amounts, there is some evidence to indicate that the oil was originally formed from sediments of another age and has migrated into its present abode. Such views are supported by the unfavorable character of the strata in which the oil is found. All rocks of sedimentary origin laid down during or after the Cambrian period must be considered as potential sources of oil until examination or drilling has proved them non-petroliferous.

The close of the Proterozoic was characterized by wide emergence of the continents and mountain building movements of major importance and world wide extent. The finding of tillites and glacially striated boulders in the deposits of Middle and Late Proterozoic in North America, Asia, Africa, and Australia, indicates the existence of glacial conditions throughout much of the world at the end of the Proterozoic. Some authorities consider that the glacial conditions continued into the Cambrian, but it seems to be more generally believed that wide-spread glaciation ended before Cambrian deposition began. However, much of North America and other continents was probably still comparatively high land and subject to erosion during the early part of the Cambrian.

Two synclines of major proportions developed in North America early in the period. These were the Appalachian and the Cordilleran geosynclines. At first they were comparatively narrow and relatively deep. The first extended from the region of the Gulf of St. Lawrence to the Gulf of Mexico; the second, from the Arctic southward to Lower California. During the middle and later portions of the period, the waters of these troughs spread out over much of the central portions of the continent, deposits reaching considerable thickness in the Mississippi and Ohio Valleys. Similar transgressions of the seas upon other continents are known and have been studied carefully in Europe.

A limited quantity of gas is considered as coming from the Cambrian strata of western New York. Non-commercial quantities of oil have been obtained in Newfoundland and Nova Scotia from rocks which are believed to be of the same age. There is no other evidence of oil in rocks of this age. The abundance of rocks consisting of carbonate of lime, especially in Middle and Upper Cambrian strata, and the prolific nature of the fauna of invertebrate marine animals with lime skeletons indicate a mild and equable climate. The fauna, while including representatives of the main stocks or phyla of the marine invertebrates, shows only the simpler forms. This is natural for a period so early in the earth's history and one that follows so closely after widespread glaciation and abnormally low temperatures. There is no evidence to indicate the existence of land plants or animals in the strata of this period. The existence of lower forms of such life, or at least of plants in the lowland is considered probable. There is no reason to believe that sufficient life was developed in protected shallow fresh and semi-fresh water basins to produce oil-forming debris.

Many of the rocks of this age are partly or wholly metamorphosed. The metamorphism in others has not progressed far, but the reduction of pore space is generally considered to preclude their containing commercially valuable amounts of oil. Exceptions to this should be noted. W. J. Miller[1] states: "In eastern and central Europe, for example Russia, the strata are mostly practically horizontal and even unconsolidated beds of sands and clay have been found."

Ordovician History.--The Cambrian system was followed by the Ordovician. This was of greater duration and should be subdivided for careful study. In North America there were three distinct periods of submergence of the largely worn down continent. The first of these was of shorter duration and smaller extent than the last two. Its existence is shown by the presence of thickly bedded dolomites in

[1] Introduction to Historical Geology, p. 68, 1916.

the Appalachian trough. This was the most important area of deposition in North America at this time. The reflooding of the continent during Middle Ordovician followed different lines than that of the early portion of the period and the Cambrian. The north-south troughs were no longer continuous water areas but were divided by uplifts in the region of the Gulf of St. Lawrence and in Montana, southern Alberta, and Saskatchewan. The waters of the Appalachian trough were extended westward to Oklahoma, Kansas, and northern Texas, and northwest to flood the central plains of Canada and join with the Arctic.

The Middle Ordovician of the Ohio Valley is probably the best known to the oil geologist because it contains the Trenton horizon. The Trenton formation is composed of thin bedded limestones interbedded with dark shales.

The last of the floods of the period was largely a repetition of the second, with the exception that for some time the St. Lawrence-Gulf of Mexico connection was reestablished and that the waters did not extend as far to the west in the central states. While shales were of increasing importance and sandstones appeared in large amounts as the last of the three floods ebbed, the thin bedded limestone still remained the dominant sediment until the close of the period.

Much of Europe appears to have been submerged during the Ordovician, but the submergence can hardly have been as marked as in North America. Limestones are relatively scarce in Europe.

Throughout all but the very last portion of the period, a warm and equable climate existed in North America and probably throughout the whole of the Northern Hemisphere. Less is known of conditions in the Southern Hemisphere. The close of the Ordovician was accompanied by little crustal disturbance other than direct uplift in eastern North America. In the British Isles and probably in the western portion of Europe, Middle and Upper Ordovician time was one of intense volcanic and plutonic action. Sediments in those areas were highly metamorphosed. Similar action occurred in Australia.

Ordovician Oil.—The Ordovician is the first of the world's great oil reservoir periods. Luther White[1] considers the "Turkey Mountain Sand or Siliceous Lime" oil horizon of Oklahoma as being the upper and eroded surface of the Arbuckle limestone. He calls this Cambro-Ordovician. Above this horizon, oil is obtained from the Wilcox sands, the Burgen sandstone, and sand lenses in the Tyner formation, which are considered as of Simpson age and placed in the Ordovician period.

---

[1] Petroleum Development and Technology in 1925, p. 585.

Until recently the oldest productive horizon in the Eastern Province of the United States was considered to be the Trenton limestone, a formation laid down during the latter part of the second transgression of the sea. It is the source of oil in the Lima-Indiana district and is productive in other parts of the east. Development in Kentucky and Tennessee has shown the existence of paying quantities of oil immediately below the Trenton in limestones considered to belong to the Stones-River group. These are still Middle Ordovician in age. Above the Trenton are several producing horizons in Kentucky. These are placed in the Upper Ordovician.

While the wide-spread occurrence of oil in rocks of Ordovician age suggests that it was original with the limestones or the shales of that age, there seems to be considerable feeling among petroleum geologists that much of the oil was originally formed in the Devonian or Chattanooga black shales and has migrated downward into the older rocks. Luther White[1] suggests that the absence or presence of oil in some of the deeper Ordovician beds in Oklahoma may be due to the absence or presence of porous beds capable of absorbing the oil lying between the Chattanooga (Devonian) shale and these beds. The well records of both the Mid-Continent and the Eastern Provinces show but limited amounts of dark colored shales in the Ordovician. Dark colored limestones are more common, but their value as original sources of oil is questioned.

Silurian History.—In general the Silurian was marked in North America by continental emergence. Except for a single epoch of flooding in the middle of the period, seas were never comparable in extent with those of the Ordovician. Silurian strata are generally absent west of the Mississippi River. Erosion was probably long continued in this area. Except during the last part of the period the climate in North America was warm, moist, and equable. Land plants and animals, together with fresh water marine life, have left sufficient fossil records to prove their wide-spread occurrence. The shallowing and restriction of the epeiric seas undoubtedly restricted life of the marine type. While the marine fauna was still prolific, it was not as varied as that of the Ordovician. In the Appalachian trough the Lower Silurian deposits consist of cross-bedded sandstones, sandy and calcareous shales, and öolitic and fossiliferous iron ores.

---

[1] Idem, p. 591.

The comparatively brief submergence during the middle of the period was accompanied by the deposition of limestones, now of dolomitic character. The later part of the period was marked by reduction of the seas and the development of arid conditions in New York, Ohio, Ontario, and Michigan. Salt and gypsum were characteristic deposits in these areas at this time. Immediately above these and occupying a considerably larger area are deposits of clay-limestone or cement rock. This is sun cracked and otherwise indicative of shallow water conditions.

There is reason to believe that the Middle Silurian flood was due to great mountain building movements throughout the Old World and in South America, which caused a surplus of water to flood the low lying eastern lands. Evidence of glaciation during the Late Silurian has been found in Alaska and British Columbia.

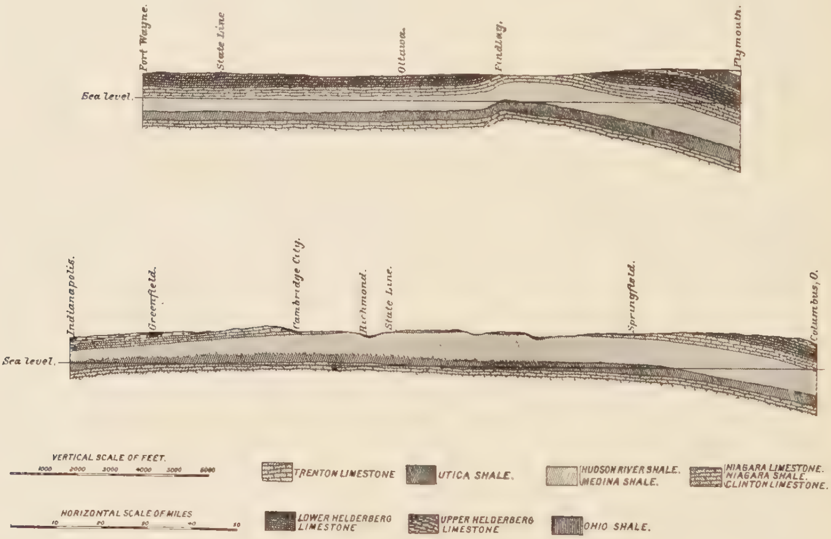


FIG. 10.—East-west section across the Cincinnati Arch in Ohio and Indiana. After Orton, E.: U. S. G. S. 8th Annual Report, Part 2, Plate LVIII, 1889.

Silurian Oil.—Silurian formations are much less common in North America than those of Ordovician age. Unless the Hunton limestone, which has been tentatively called Siluro-Devonian by Oklahoma geologists, is considered as Silurian, the production of oil and gas from this period is obtained only in the rim areas of the Appalachian trough and in the overlap sections immediately west of it. Sand beds in the Medina shales of Lower Silurian are productive of gas and oil in New York and Ontario. The Clinton formation of Middle Silurian is an important producing horizon in parts of Ohio. The Niagaran formation of Upper Silurian age is productive over a wide area in Kentucky and yields some oil in New York, Ontario, and Indiana.

The Cincinnati Uplift.—The lateral extent of the Silurian formations in the east and the manner of the movement of the oil in the porous horizons were largely due to the development of the Cincinnati uplift. This began in the later portion of the Ordovician. During Early Silurian this geoanticline definitely separated the interior basin into two divisions: one to the east, and the other to the west of a line running north and south through western Ohio. During Middle Silu-

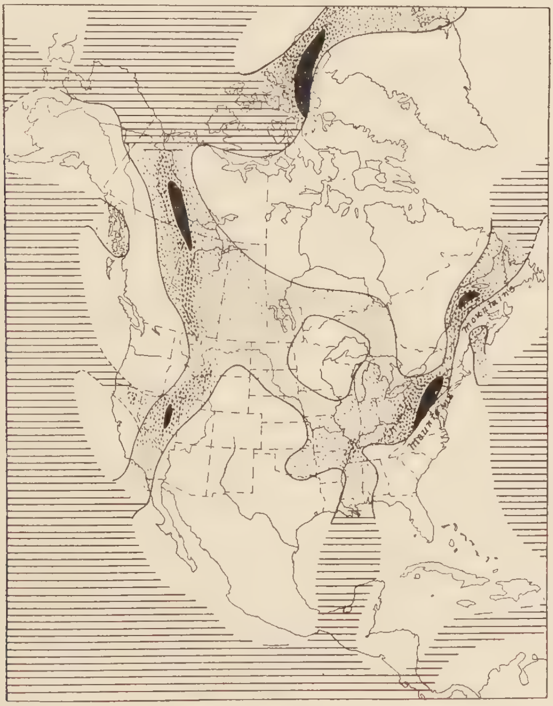
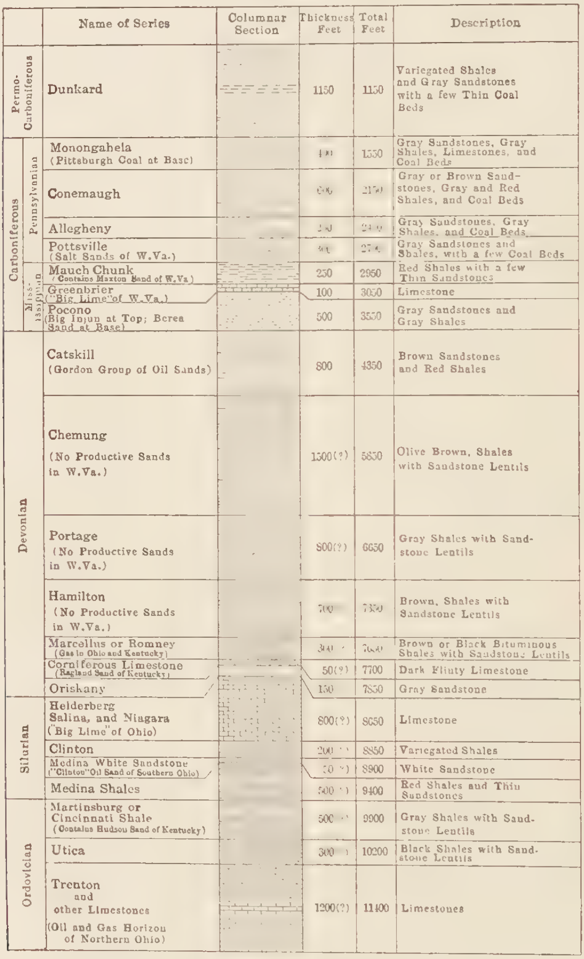


FIG. 11.—Geosynclines, Embayments, and their Extensions during Devonian Time in North America. Shading indicates areas of greatest subsidence. After Schuchert, C.: Geol. Soc. Amer. Bull., Vol. 34, p. 220, 1923.

rian the central portion of the arch was submerged below the level of the seas, leaving only two islands above the water. These from their location were known as Nashville and Cincinnati islands. The islands persisted throughout the later part of the Silurian but were finally base-leveled and covered with sediments in the Devonian. However, they continued to influence deposition throughout the whole of the Paleozoic. Their outlines are clearly shown by outcropping strata today.



		Name of Series	Columnar Section	Thickness Feet	Total Feet	Description
Permo-Carboniferous		Dunkard		1150	1150	Variegated Shales and Gray Sandstones with a few Thin Coal Beds
Carboniferous	Pennsylvanian	Monongahela (Pittsburgh Coal at Base)		400	1550	Gray Sandstones, Gray Shales, Limestones, and Coal Beds
		Conemaugh		600	2150	Gray or Brown Sandstones, Gray and Red Shales, and Coal Beds
		Allegheny		300	2450	Gray Sandstones, Gray Shales, and Coal Beds
		Pottsville (Salt Sands of W.Va.)		250	2700	Gray Sandstones and Shales, with a few Coal Beds
	Mississippian	Mauch Chunk (Contains Maxton Sand of W.Va.)		250	2950	Red Shales with a few Thin Sandstones
		Greenbrier ("Big Lime" of W.Va.)		100	3050	Limestone
		Pocono (Big Injun at Top; Berea Sand at Base)		500	3550	Gray Sandstones and Gray Shales
Devonian		Catskill (Gordon Group of Oil Sands)		800	4350	Brown Sandstones and Red Shales
		Chemung (No Productive Sands in W.Va.)		1500(?)	5850	Olive Brown, Shales with Sandstone Lentils
		Portage (No Productive Sands in W.Va.)		800(?)	6650	Gray Shales with Sandstone Lentils
		Hamilton (No Productive Sands in W.Va.)		700	7350	Brown, Shales with Sandstone Lentils
		Marcellus or Romney (Gas in Ohio and Kentucky)		300(?)	7650	Brown or Black Bituminous Shales with Sandstone Lentils
		Corniferous Limestone (Ragland Sand of Kentucky)		50(?)	7700	Dark Flinty Limestone
		Oriskany		150	7850	Gray Sandstone
Silurian		Helderberg Salina, and Niagara ("Big Lime" of Ohio)		800(?)	8650	Limestone
		Clinton		200(?)	8850	Variegated Shales
		Medina White Sandstone ("Clinton" Oil Sand of Southern Ohio)		50(?)	8900	White Sandstone
		Medina Shales		500(?)	9400	Red Shales and Thin Sandstones
Ordovician		Martinsburg or Cincinnati Shale (Contains Hudson Sand of Kentucky)		500(?)	9900	Gray Shales with Sandstone Lentils
		Utica		300(?)	10200	Black Shales with Sandstone Lentils
		Trenton and other Limestones (Oil and Gas Horizon of Northern Ohio)		1200(?)	11400	Limestones

FIG. 12.—Section of the Paleozoic rocks of the central portion of the oil areas of West Virginia. After Reger, D. B.: A. I. M. E. Trans., Vol. 56, p. 860, 1916.

Devonian Conditions.—As in the case of rocks of the earlier parts of the Paleozoic, our knowledge of the Devonian has been gained largely from study of the deposits of the eastern states. Early Devonian was not unlike the last part of the Silurian in this area. Despite the narrow limits of the two basin areas on either side of the Cincinnati Arch, their deposits were largely limestones. In the far west, the Cordilleric or Rocky Mountain trough seems to have been well developed and to have been a center of lime deposition throughout the whole of the period. Early in Middle Devonian the connection between the Atlantic in the region of the St. Lawrence and the Gulf of Mexico seems to have definitely ended. In the middle of the period the waters of the Cordilleran Sea spread slowly northward and eastward to unite first, with the waters of the Arctic, and later, in Upper Devonian, with those of the eastern basin. This produced a more or less continuous body from the Pacific to the Appalachian area and from the middle west to the Mackenzie Valley of Canada.

While shales were uncommon in the middle of the period, they became the dominant type of deposits during the last half of the period throughout much of the submerged area. Along the eastern edge of the Appalachian trough, that is, in western Virginia and Maryland, central and eastern Pennsylvania, and eastern New York, tremendous thicknesses of fresh and brackish water delta deposits were laid down. In the land masses immediately east of this belt, mountain building movements occurred.

Early Devonian seems to have been characterized by wide-spread uplift and folding throughout Oklahoma and adjacent states. This period of uplift was followed by one of erosion and base leveling which did not end until the close of the Devonian. Thus while the record of this period is one of practically continuous sedimentation throughout the Appalachian basin, it is represented by a very thin and incomplete section in the Mid-Continent area. The Chattanooga brown and black shales, in which the bulk of the Pre-Pennsylvanian oil of Oklahoma is believed to have originated, appear to have been laid down in the Early Mississippian rather than in the Late Devonian as had been originally believed.

Despite the emergence of wide areas in Europe and the North Atlantic area, Devonian time seems to have been characterized by a mild climate. The rapid spread and development of animal and plant life upon the continents indicates that while semi-arid conditions may have existed in many of the highly uplifted areas, there were others

TABLE 32.—OIL HORIZONS OF THE PENNSYLVANIA-WEST VIRGINIA OIL DISTRICTS.*

	Distance above (+) or below (−) the Pittsburgh coal in feet
Carboniferous.	
Pennsylvanian.	
Monongahela formation (Upper Productive measures).	
Carrol sand (Uniontown sandstone), productive in West Virginia only	+ 300
(Pittsburgh Coal horizon)	
Conemaugh formation (Lower Barren measures).	
Murphy, Shallow, Little Dunkard, or First Cow Run sand (Saltsburg sandstone)	− 200
Big Dunkard or Cow Run sand (Mahoning sandstone)	− 500
Allegheny formation (Lower Productive measures).	
Second Cow Run sand (Freeport sandstone)	− 600
Gas sand	− 800
Pottsville formation (Salt sand).	
Johnson Run sand (Homewood sandstone)	− 900
Upper Salt sand (Lower Conoquenessing sandstone)	− 950
Middle Salt sand (Lower Conoquenessing sandstone)	−1,050
Lower salt (Sharon conglomerate)	−1,150
Mississippian.	
Mauch Chunk formation.	
Maxton or Cairo sand (of West Virginia)	−1,200
Greenbrier limestone ("Big Lime")	−1,250
Pocono formation (Big Injun sand).	
Keener sand	−1,300
First, Second, and Third Pay sands (Top)	−1,400
Squaw sand	−1,450
Wier sand	−1,500
Devonian.	
Catskill formation.	
Upper Gas sand (sometimes placed in Pocono)	−1,550
Berea or Thirty-foot sand (sometimes placed in Pocono)	−1,750
Murraysville or Butler sand	−1,800
Gantz, First, or Hundred-foot sand	−1,850
Fifty-foot sand	−1,900
Ninevah, Thirty-foot, or Second sand	−2,000
Gray, Gordon Stray, or Boulder sand	−2,100
Gordon, Third, or Campbells Run (?) sand	−2,150
Fourth sand (Gordon of West Virginia?)	−2,200
Fifth sand (McDonald of West Virginia?)	−2,250
Bayard sand	−2,400
Chemung formation.	
Elizabeth or Sixth sand	−2,600
Warren First sand	−2,700
Warren Second sand	−2,800
Tiona sand	−2,900
Speechley sand	−3,000
Balltown or Cherry Grove sand	−3,120
Sheffield or Cooper sand	−3,320
Bradford sand	−3,430
Second Bradford sand	−3,480
Elk sand	−3,650
Kane sand	−3,770

* After Fuller, M. L.: Geol. Soc. American Bull., Vol. 28, p. 633, 1917.

in which all of the conditions were favorable to life. While not of commercial value, coal beds indicate the existence of coal forming swamps of local extent in Norway and Scotland during the Devonian. In the shallow upper Devonian seas, black muds or shales were deposited in varying thickness from Pennsylvania westward to Oklahoma and from Tennessee northward to the Mackenzie Valley. Of course, these shale beds were not formed continuously over the whole area, and erosion has removed much of the original shale from others.

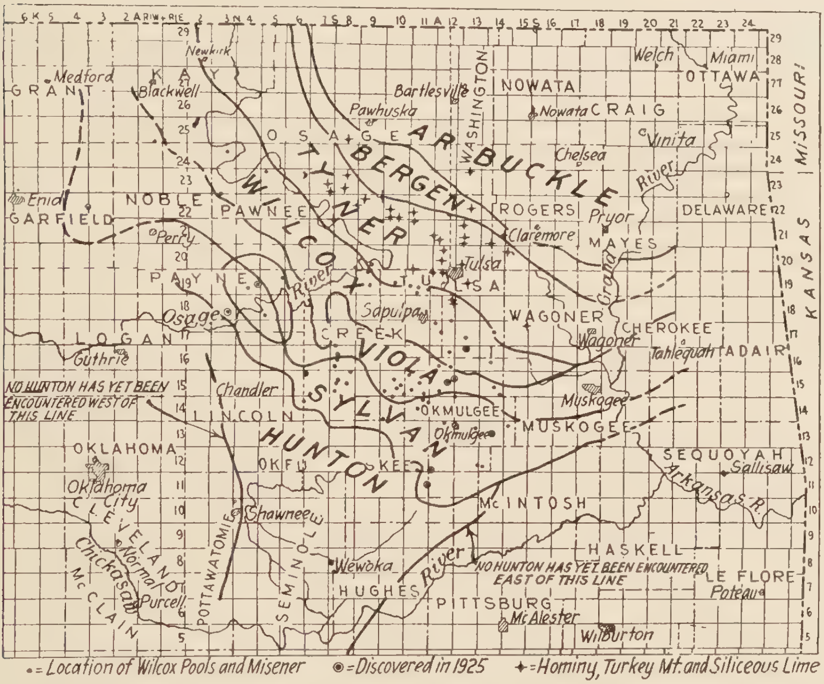


FIG. 13.—Map showing geographic distribution of Pre-Chattanooga rocks and oil pools in Northeastern Oklahoma. The map may be considered as the surface geology map of the area at a time immediately preceding the beginning of the deposition of the Chattanooga shales. After White, Luther H.: Pet. Dev. and Tech. in 1925, p. 586.

Devonian as a Source of Oil.—Excluding the Hunton lime, whose age is still in doubt, limestones of Lower Devonian age have proved of little interest to the oil geologist. The Corniferous limestone and the Hamilton formation of Middle Devonian are of considerable importance in the Appalachian syncline east of the Cincinnati Arch.

The greatest production of the Devonian comes from sands of the Upper Devonian. These are sand lentils of considerable thickness and areal extent in the black shales of northwestern Pennsylvania and western New York. Similar lentils, but of slightly younger age, are productive through southwestern Pennsylvania and West Virginia. Production from all of these sand horizons may be considered as coming from the equivalent of the Chattanooga shale, although that formation reaches a thickness of more than 4000 feet in parts of the oil producing areas of Pennsylvania and decreases to less than 50 in sections of southern Kentucky, and Tennessee. Some oil has been secured from similar sands in the Mackenzie Valley of Canada.

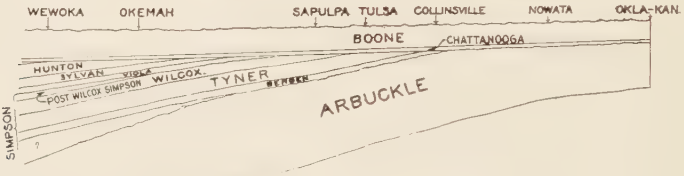


FIG. 14.—Cross-section of Northeastern Oklahoma, showing geographical distribution of Pre-Chattanooga rocks. After White, Luther H.: Petroleum Development and Technology in 1925, p. 590.

While at first sight the Devonian of the Mid-Continent area seems to have very little importance to the oil geologist, this is far from true. The long period of erosion which followed the uplift and folding in the Late Silurian or Early Devonian served as a period of preparation whose importance can hardly be estimated. Sandy formations were exposed and limestones eroded and water channeled so that they could function as containers for the oil which was to be supplied to them somewhat later from the Chattanooga shales.

Mississippian Conditions. While the end of the Upper Devonian was characterized by wide-spread retreat of the seas, the line of demarcation between the black shales, which are definitely of that age and those that, owing to paleontological evidence, are considered as Lower Mississippian, is very indistinct. Thus, while the Chattanooga of the Eastern Province is considered as Devonian, the Chattanooga of Kansas and Oklahoma is commonly considered as being the base of the Mississippian. East of the Cincinnati Arch the filling of the Appalachian trough continued into the Mississippian. Sandstones, conglomerates, shales, and thin coal beds indicate the continued rapid erosion of the Appalachian land mass. West of the Cincinnati Arch and particularly west of the Ozark area, the tendency was toward submergence. Lime formation continued between the arch and the Ozark area during the first half of the period, but later sediments in this section were largely of detrital material. In the extreme west, the Cordilleran syncline became deeper and broader, finally spreading over much of the area of the Great Plains. This produced a continuous body of water from the Cincinnati Arch to the Pacific and the Arctic Oceans, interrupted only by the presence of such elevated areas as Llano and Ozarkia and scattered islands throughout the Rockies.

In the later part of the period the Cordilleran Sea was greatly restricted, and its waters separated from the rapidly shallowing seas of the upper Mississippi Valley. Salt and gypsum were laid down in the cut-off South Michigan lagoon, and shales and shaly limestones, in southern and eastern Oklahoma, northern Texas, and Illinois. The stratigraphy of central and southern Oklahoma was complicated by the development of a marked area of emergence during Mississippian time. This extended from Alabama westward through the Quachita, Arbuckle, and Wichita Mountain areas. This section was subjected to several periods of uplift followed by erosion and complicated by some submergence. Thus, while largely covered by water during parts of the Pennsylvanian, it divided the large Mid-Continent Basin into two basins: one to the north, the other to the south.

Mississippian Oil.—The Mississippian is a period of first rank as a producer of oil and gas in the United States. However, much of the so-called ''Mississippi lime'' production in Oklahoma and Kansas has been proved to be of older age. The absence of representatives of the upper shaly Mississippian beds in northeastern Oklahoma leads to the belief that it has been removed by erosion from that section. However, Mississippian limestones are responsible for the production of many of the deeper wells in Osage County and adjacent areas in northern Oklahoma and eastern Kansas. The Lower Mississippian of the Appalachian trough is one of the major producing horizons of Kentucky, eastern Ohio, and West Virginia. The Late Mississippian is the source of much oil in Illinois and western Indiana. The source of the oil in these various areas may be considered as either the early Mississippian or late Devonian Chattanooga shale, or its equivalent, or as the shale beds in the Middle and Upper Mississippian.

TABLE 33.—GENERALIZED STRATIGRAPHIC COLUMN OF THE PALEOZOIC OF EASTERN KANSAS AND NORTHEASTERN OKLAHOMA. (Correlations of producing horizons approximate.)*

	KANSAS			OKLAHOMA			
Series	Formation	Member	Producing Horizon	Formation	Member	Producing Horizon	Correlated With
Permian	Greer	Big Basin sandstone Hackberry shale		Greer			
	Woodward	Day Creek dolomite Whitehorse sandstone Dog Creek shale		Woodward	Day Creek dolomite Whitehorse sandstone Dog Creek shale		
	Cave Creek	Shimer gypsum Jenkins shale Med. Lodge gypsum		Blaine	Shimer gypsum Jenkins shale Med. Lodge gypsum		
	Enid	Flower Pot shale Cedar Hills sandstone Salt Plain shale Harper sandstone		Enid			
	Wellington			Wellington			
	Marion	Abilene conglomerate Pearl shale Herington limestone Enterprise shale Luta limestone		Chase	Herington limestone Uncas shale		
	Chase	Winfield limestone Doyle shale Fort Riley limestone Florence flint Matfield shale Wreford limestone		Blackwell	Winfield limestone Doyle shale Fort Riley limestone Matfield shale Wreford limestone		
Base of Permian?	Council Grove	Garrison limestone and shale Cottonwood limestone		Blackwell	Crouse limestone Cottonwood limestone		

TABLE 33.—*Continued*

	KANSAS			OKLAHOMA			
Series	Formation	Member	Producing Horizon	Formation	Member	Producing Horizon	Correlated With
Base of Permian? Pennsylvanian	Wabaunsee	Eskridge shale Neva limestone			Neva limestone Red Eagle limestone Foraker limestone	800 feet gas sand at Tonkawa	
		Elmdale shale Americus limestone Admire shale Emporia limestone Willard shale Burlingame limestone				1,400 feet gas sand at Tonkawa	
	Shawnee	Scranton shale Howard limestone Severy shale Topeka limestone Calhoun shale Deer Creek limestone			Pawhuska limestone	Newkirk sand (gas)	1,400 feet gas at Blackwell; 2,000 feet gas at Deer Creek
		Tecumseh shale Lecompton limestone Kanwaka shale	Elgin sands	Elgin sands		Upper Hoover Lower Hoover	2,400 feet gas at Deer Creek
	Douglas			Buxton		Ponca sand	Tonkawa sand and Stalnaker
	Lansing			Wilson			
	Kansas City		Gas sands	Ramona			
			Stray sands	Curl		Layton sand	Layton sand
	Marmaton	La Cyne shale Lenapah limestone Nowata shale	Old Red sand		Lenapah limestone Nowata shale	Wayside Jones McEwen Cleveland Big lime	
					Oolagah		
		Altamont limestone Bandera shale Pawnee limestone Labette shale Fort Scott limestone	Peru sand Oswego sand		Labette shale Fort Scott	Peru sand Oswego lime	Wheeler Swenson and Claremore

TABLE 33.—*Continued*

	KANSAS			OKLAHOMA			
Series	Formation	Member	Producing Horizon	Formation	Member	Producing Horizon	Correlated With
	Cherokee shale		Undifferentiated sands	Cherokee shale			
						Prue sand	Squirrel, Bixler and Perryman
						Skinner sand Red Fork sand Nemire sand Sand	
			Bartlesville sand			Bartlesville sand	Glenn gas of Morris salt and Burbank
						Tucker sand	Booch Squaw Meadows Tancha Dutcher (called Burgess in places)
						Deaner sand	Glenn of Morris Gilcrease, Youngstown, Preston, Rhodes
Unconformity			Burgess sand			Burgess sand	Sand on top lime
Mississippian	Boone limestone		"Chat" horizon	Mississippi Lime	Pitkin Caney	Top of lime	
Unconformity Devonian and Silurian	Chattanooga Hunton		Misener sand	Chattanooga Hunton		Lyon sand? Misener sand Wilcox sand at Mounds and Sapulpa under Chattanooga †	Cromwell Papoose
	Sylvan shale			Sylvan shale			
Unconformity	Viola limestone			Viola limestone			
Ordovician	Simpson	Wilcox sand Tyner formation Burgen sandstone	Wilcox sand	Simpson	Post Wilcox † Wilcox sand Tyner formation Burgen sandstone Lower Simpson	Hominy "Wilcox"	At Okemah, Wewoka, Cromwell and Seminole
Unconformity Ordovician and Cambrian	Arbuckle limestone		Siliceous lime	Arbuckle limestone		Siliceous lime	Turkey Mountain
Cambrian	Reagan sandstone			Reagan sandstone			
Unconformity Pre-Cambrian	Granite			Granite			

* After Peterson, C. J.: Oil and Gas Journal, June 16, 1927, p. G–119.

† After Luther H. White: Subsurface Distribution and Correlation of the Pre-Chattanooga ("Wilcox" sand) Series of Northeastern Oklahoma. Oklahoma Geological Survey Bull. No. 40-B.

Pennsylvanian History.—Pennsylvanian time was similar to Mississippian in many respects. While the limited extent of early Pennsylvanian seas and their connection with the Pacific through the waters of the Gulf of Mexcio rather than by water areas directly to the west indicate differences, the two periods were apparently not separated by crustal movements of any great extent. The end of the Lower Pennsylvanian was characterized by more or less continuous swamp or marsh conditions extending from Pennsylvania southward to Alabama and westward to Oklahoma and Texas. The latter part of the period showed continued oscillation of the strand line. The low-lying Cordilleran areas were again subjected to submergence and thick limestones were laid down. These are in distinct contrast to the sands and shales which predominate in the Mid-Continent and Eastern Provinces. As the building of the Appalachian Mountains in the

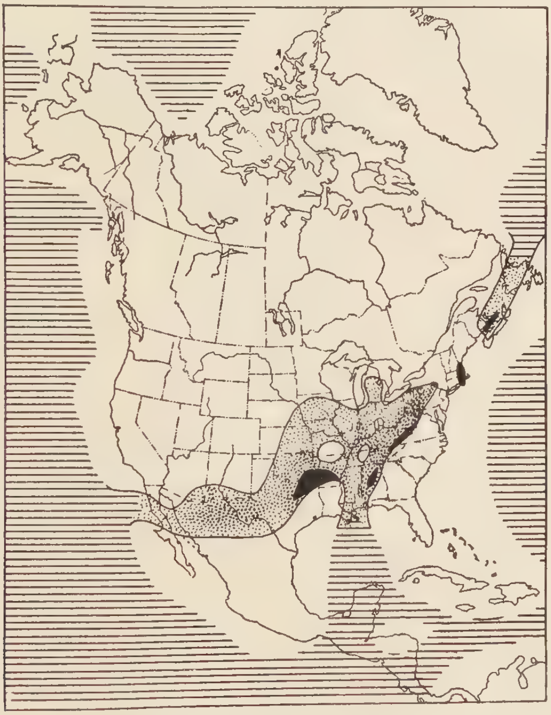


Fig. 15.—Seas and Swamps of Early Pennsylvanian Time in North America. Shading indicates areas of greatest subsidence. After Schuchert, C.: Geol. Soc. Amer. Bull., Vol. 34, p. 223, 1923.

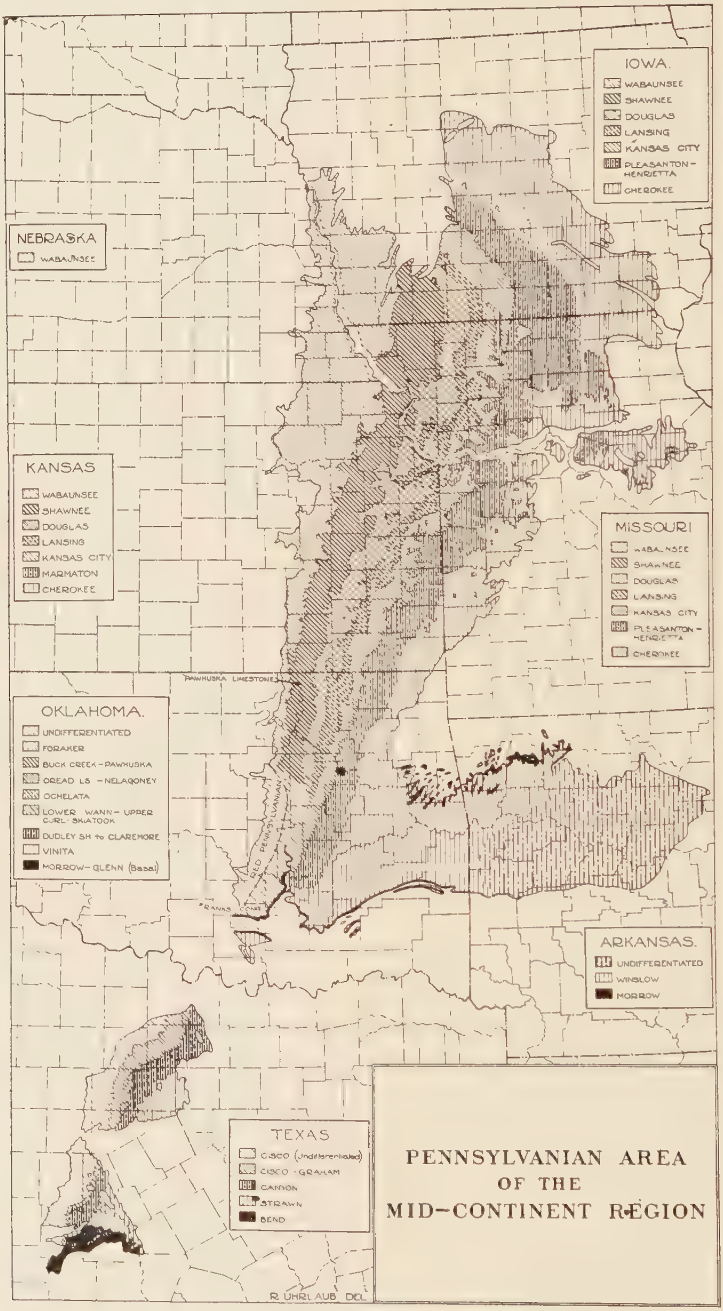


FIG. 16.—Map showing distribution of Pennsylvanian outcrops in the Eastern Mid-Continent Region. The size of the westward dipping monocline is clearly indicated. After Moore, R. C.: A. A. P. G. Bull., Vol. 9, p. 47, 1922.

eastern portion of the United States continued throughout the whole of the period and was accompanied by similar mountain building movements in all of the other continents, it is probable that the continued submergence of the western lowlands was due to the inability of the ocean basins to contain the waters given back to them rather than to subsidence of the area itself. In Colorado, a predecessor of the present East or Front Range of the Rockies was built up.

Pennsylvanian time is noted for the luxuriant plant and animal life which existed throughout the period. Not only is the evidence of that life contained in marine strata but also in fresh water and swamp deposits. In Europe, the general emergence of the continent began earlier than in North America. Its deposits are more definitely of continental nature and less commonly of the open water basin types most prevalent throughout the Mid-Continent areas. While black and dark colored shales are found interbedded with coal seams, the greatest value of the Pennsylvanian as an oil producing period is found where the strata are more dominantly those of the epeiric sea than the continental swamp.

Pennsylvanian Oil.—The limited quantity of oil found in Great Britain comes from the Lower Carboniferous rather than the Pennsylvanian coal measures. Pennsylvanian sands and conglomerates are productive in the Appalachian trough but are of much less importance than the horizons of lower age which lie below them. In the Illinois field the Pennsylvanian is an important horizon, but the bulk of the oil comes from strata below the important coal beds. Some is secured in the Upper Mississippian. Pennsylvanian strata are of major importance in Oklahoma, Kansas, and North Texas, where the Cherokee, Glenn, and Smithwick shales, deposited in the early portion of the period, serve as the chief source beds. Numerous less extensive and thinner beds of shale probably serve as the source beds for the oil contained in the younger Pennsylvanian strata.

Permian Conditions.—The Permian period marks the close of the Paleozoic era and with it the end of deposition of coal and oil forming debris in the Eastern and Mid-Continent basinal areas of the United States. The period was marked by the culmination of the great mountain building movements initiated in earlier periods in every continent of the globe. The waters of the epeiric seas were restricted to the basins of the oceans. Glaciation existed throughout many areas of the globe and was particularly in evidence in the southern hemisphere. Early in the period salt and gypsum deposition began in

Table 34.—Classification of the Texas-Pennsylvanian.*

		Thickness in Feet	Colorado River Valley	Brazos River Valley
Cisco Group	Putnam formation	125–175	Coleman Junction limestone Santa Anna Branch shale	Coleman Junction limestone Santa Anna Branch shale
	Moran formation	150–200	Sedwick limestone Santa Anna shale Horse Creek limestone = ? Watts Creek shale	Sedwick limestone Shale Dothan limestone Shale
	Pueblo formation	150–200	Camp Colorado limestone Shale Stockwether limestone = ? Camp Creek shale	Camp Colorado limestone Shale Eolian limestone Shale
	Harpersville formation	200–275	Saddle Creek limestone Shale and coal	Saddle Creek limestone Shale Belknap limestone Shale and coal Crystal Falls limestone Shale and sandstone
	Thrifty formation	100–200	Breckenridge limestone Shale "Lower Chaffin" limestone (Drake) = ? Shale "Speck Mountain" limestone (Drake) = ? Shale and sandstone	Breckenridge limestone Shale Black Ranch limestone Shale Ivan limestone Shale Avis sandstone
	Graham formation	100–600	Wayland shale Gunsight limestone Bluff Creek shale	Wayland shale Gunsight limestone South Bend shale Bunger limestone Gonzales Creek shale Jacksboro limestone Finis shale
Canyon Group	Caddo Creek formation	30–150	Home Creek limestone Hog Creek shale	Home Creek limestone Hog Creek shale
	Brad formation	175–250	Ranger limestone Placid shale Clear Creek limestone Cedarton shale	Ranger limestone Seaman Ranch shale
	Graford formation	170–450	Adams Branch limestone Brownwood shale Capps limestone bed Rochelle conglomerate	Adams Branch limestone Brownwood shale
	Palo Pinto limestone	50–100	Not present	Palo Pinto limestone
Strawn Group	Mineral Wells formation	500–800	Undifferentiated	Keechi Creek shale Turkey Creek sandstone Salesville shale Lake Pinto sandstone East Mountain shale Brazos River sandstone Mingus shale Thurber coal
	Millsap formation	1,800–3,000		Millsap formation (undifferentiated)
Bend Group	Smithwick shale	400	Undifferentiated	Present, but not exposed
	Marble Falls limestone	400–500	Undifferentiated	
	Barnett shale	0–50	Undifferentiated	

* After Moore, R. C., and Plummer, F. B.: Jour. of Geol., Vol. 30, pp. 24–25, 1922.

Europe, the salt basin extending from Ireland to Germany. While marine deposits were laid down in some places, the Permian of Europe represents largely a continuation of the salt basin and continent deposition started in the beginning of the period.

Despite the wide extent of glacial conditions, the existence of coal forming swamps in Australia, Brazil, and South Africa, is indicative of comparatively warm interglacial intervals of some length. In at least one area, the extreme southwestern and western parts of Texas, New Mexico, and adjacent states, the emergence and wide-spread aridity, which characterized the Permian in North America, did not come until late in the period. While the Permian of Oklahoma, Kansas, and North Texas, is composed almost entirely of brackish water and fresh water deposits or thick salt and gypsum beds, these do not occur before the later portions of the period in the southwest. Here the red-beds, which are so prominent throughout the whole of the Permian of Oklahoma and Kansas, are underlaid by thick and massive beds of Permian limestone. The open water conditions of New Mexico and the extreme western parts of Texas probably extended northward and westward to the west of the Pennsylvanian Rockies of Colorado into Idaho, Utah, and adjacent areas.

Permian Oil.—The major portion of the world's Permian was laid down under conditions distinctly unfavorable to the accumulation of oil forming debris. Wide-spread erosion has removed a great deal of the original Permian beds. Many sections, such as the Rocky Mountain areas of today, have been subjected to most intense crustal movements, which have either destroyed the oil that the sediments may have contained because of locally favorable conditions or permitted it to escape to the surface through fault fissures. Late Pennsylvanian red-beds and Permian red-beds do contain productive sandstones. Limestones which yield oil in the Panhandle of Northwest Texas and the Marathon fold of western Texas are undoubtedly of this period. The productive horizon of the Artesia district of eastern New Mexico is in the Permian. The Embar and equivalent horizons of Wyoming, Montana, and Utah are also classed as of Permo-Carboniferous age. The origin of the oil in these various horizons is not clear. In some it must be considered as having come from shales of the same age. In others, for example the Panhandle area, the oil has accumulated along unconformities and may have originated in strata of older age which lie deeply buried.

The Paleozoic as an Oil-yielding Era.—Up to the present the rocks of the Paleozoic era have only proved productive on a large scale in the two great basins between the Rockies and the Appalachian Mountains. Where subjected to intense alteration accompanying major crustal deformation as in the Appalachian Mountains and the Quachitas, the rocks no longer contain oil or even gas. Wide-spread erosion has removed much of the oil-bearing material originally laid down and complicated the unraveling of the history of the two major basins. Successive uplifts accompanied by crustal warping and folding have further complicated the conditions.

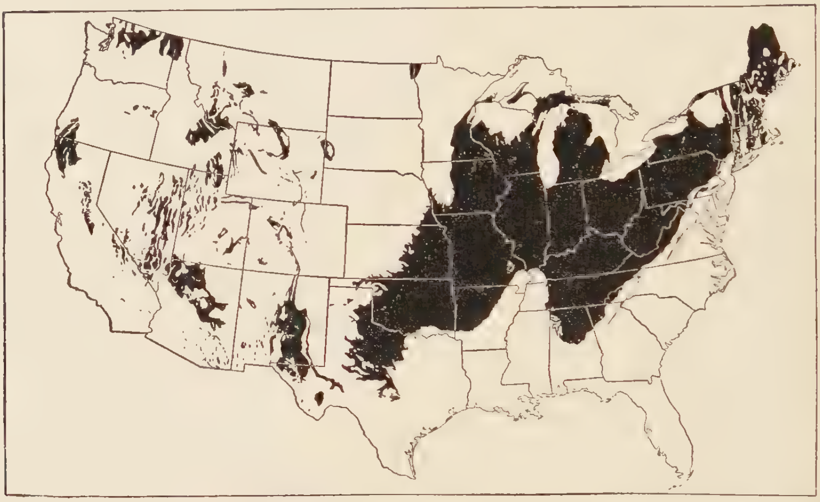


Fig. 17.—Map of the United States showing areas in which Paleozoic Rocks are at or near the surface. After Meinzer, O. E.: U. S. G. S. Water Supply Paper 489, p. 202, 1923.

The absence of evidence of volcanic action or plutonic activity throughout the two basinal areas is an important indication of the moderate character of earth movements in these areas. The Paleozoic Cordilleran syncline was undoubtedly a center of as wide-spread and varied deposition as were the areas to the east, but the later periods of orogenic movement were of such intensity and so centered as to cause the destruction and escape of the major portion of the hydrocarbons originally contained. While the periods of diastrophic action came at an earlier date, there is reason to believe that they have brought about similar conditions in western Europe and probably in other continents. While less is known of the geological conditions in these continents, it does not seem probable that Paleozoic rocks will attain the importance in them that they have today in North America.

The extension to the west and southwest of the productive areas of Oklahoma, Kansas, and North Texas, and the further investigation of the northern and less altered portions of the Cordilleran syncline lying in the Mackenzie Valley of northwestern Canada are subjects that will prove of great interest to oil geologists during the coming decade.

Mesozoic Conditions.—In North America and Europe the first of the Mesozoic periods, the Triassic, was a period of little interest to the oil geologist. While less complete, our knowledge of other continents would indicate that conditions were unfavorable to accumulation of oil source materials in them also. In North America marine strata occur only in the extreme southern and western portions. In the east, block faulting along the contact of the old Appalachian land mass and the Appalachian Mountains formed in the late Paleozoic produced a series of trough-like basins. The products of the erosion of the adjacent highlands were deposited in these. The sediments are continental in character, and from the red coloration and the presence of arkose, appear to have been laid down under arid or semi-arid conditions. The faulting was accompanied by volcanic activity. Yet conditions could not have been wholly unfavorable to life as a few thin coal beds have been found, and many fossil remains are known.

The Triassic of the Pacific states and of Central America appears to have been laid down upon submerged coastal plains rather than in true epeiric seas. In the last part of the period the Pacific waters extended farther inland, cutting off two large islands from the mainland. One of these was west of British Columbia and the other west of California. At this time the waters extended eastward into Utah, Arizona, New Mexico, Wyoming, western Colorado, and western Texas. The waters were shallow and the area so distinctly arid that red is the predominating color of the sediments and gypsum beds are of common occurrence. In the Triassic seas along the western coast, submarine volcanoes were extremely active. Limestones, together with detrital shales, were prominent near the present Pacific coast line. In southern Alaska black shales were laid down.

Triassic Oil.—These black shales may have been the source beds for the oil contained in the Jurassic rocks of southern Alaska. The Chugwater formation, a series of red shales, sands, and gypsum layers, is productive of oil in Wyoming. While it is of Triassic age, the oil that it contains is unquestionably derived from other rocks, probably from shales of earlier age. The dolomite in which the wet gas of Turner Valley in Alberta is secured has been classed as Triassic. The age of the source beds is not known definitely.

Except for these instances the Triassic of North America is not known to contain, or to have been, the source of oil. Outside of the continent the evidence is equally unfavorable, both because of the limited occurrence and unfavorable character of the sediments, and because of the lack of seepage or other indications from Triassic rocks.

Jurassic Conditions.—The Jurassic of North America and of Europe offer very different pictures. In Europe the record is that of long continued deposition on a largely sea-covered continent. Limestones were the most prominent of the deposits laid down during the period in that area. Black shales were common in parts of western Europe. Up to the present, however, only one minor area, that of Hanover in Germany, has been productive of oil. In this area faulting is prominent and the amount of residual asphalt contained in the rocks suggests that the lighter constituents of the oils have escaped or their character been altered by ground waters. German oil is of asphaltic quality. Jurassic limestones filled with asphaltic or bituminous matter are of frequent occurrence in France as well as Germany, but there is little to indicate that they still hold commercial quantities of liquid oils. Just as the Paleozoic areas of deposition in the Cordilleran syncline of the West were centers of intense crustal disturbances, so those of Jurassic age were the centers of action in Europe. The escape of oils through the open fissures resulting from intense faulting and folding has apparently removed the bulk of the oil formerly contained.

In North America the Jurassic may best be considered as a period of preparation for the Cretaceous, which follows. In the east and Gulf states, the work of erosion continued without interruption. The early Jurassic deposits of the West show that the remnants of the Pacific overlap were still in existence. After a comparatively wide but short invasion of the land by the waters of the Arctic during the middle of the period, the western portion of the continent was uplifted and a series of north-south trending mountain ranges built up, extending from Alaska to southern Mexico. The rapid retreat of the seas left wide areas in Wyoming, Colorado, and adjacent states in which the drainage was poor. In these areas fresh water deposits were laid down in the later part of the Jurassic. The waters of the Arctic invasion were characterized by a cool water fauna.

The element of greatest importance to oil formation was the development of a broad basinal area to the east of the mountains. This extended from the mouth of the Mackenzie to the Isthmus of Tehuantepec. The submergence of this area was largely the work of the Cretaceous; but Yucatan, the Isthmuthian area, and eastern Mexico were largely submerged before the end of the Jurassic. They remained submerged through the transition into the Cretaceous. The volcanic activity that began in the Triassic along the Pacific coast continued through the Jurassic.

Oil in the Jurassic.—The small production from the Jurassic of southern Alaska has been mentioned. In Wyoming, the Sundance formation of this period is a source of some oil. In northern Montana, the Ellis formation of the Upper Jurassic forms the chief producing horizon. The productive bed here is a sandstone, which rests unconformably upon the massive Madison limestone. This is of Lower Mississippian age. The Ellis contains some shaly black limestone, which may be the source of the oil. This is not definitely proved to be the case, however. Some oil has been obtained in the Jurassic at Neuquen in Argentina. The small Hanover district in Germany yields oil from Jurassic rocks.

Lower Cretaceous History.—Except for the flooding of the Great Valley of California and its extensions in British Columbia and Lower California by waters from the Pacific, which turned the Coast Ranges into islands, and the invasion of the Arctic, which reached as far as Montana for a short time, Lower Cretaceous history in North America is largely the history of the development of the Comanchean sea of Mexico. This sea, during its greatest extent, submerged all except the extreme western portion of Mexico and extended as far northward as Wyoming. For a short time it connected with the Atlantic, flooding northern Florida, southern Georgia, and Mississippi, and extending up the Atlantic coast to North Carolina. In eastern Mexico, great thicknesses of Lower Cretaceous limestones occur. During the middle of the invasion of northwestern Mexico and the western plains of the United States, the deposits were largely limestones; but, both before and after that, the deposits were those of areas close to land. The sediments filling the troughs parallel to the Pacific were composed almost entirely of detrital material. The southern portion of the Arctic embayment became extremely shallow toward the end of the Lower Cretaceous, giving rise to the formation of the Kootenai fresh water series. In southern Alberta and southeastern British Columbia, this series contains a number of workable seams of coal.

In Europe during the Lower Cretaceous, the seas, which at the close of the Jurassic had largely retreated, again spread over the

Table 35.—Sedimentary Formations in Central Montana.*

Geologic age		Group and formation		Thickness (feet)	Character
Cenozoic.	Recent.	Alluvium.		0–50±	Flood-plain and alluvial-fan deposits of clay, sand, and gravel.
	Pleistocene	Glacial drift.		1–10	Boulders and gravel of granite, other igneous rocks, and limestone.
		Bench gravel.		10–50	Deposits of gravel and sand forming flat-topped benches.
	Eocene.	Fort Union formation.		1,850–1,950	A nonmarine sandy formation containing massive sandstone, buff and gray shale, and coal beds.
	Eocene (?)	Lance formation.		820	A brackish to fresh water sandy formation containing brown and gray sandstone, shale, clay, and earthly lignite.
Mesozoic.	Upper Cretaceous.	Montana group.	Bearpaw shale.	1,000–1,200	Steel-gray to black and greenish-black marine shale containing beds of bentonite and lumpy concretions.
			Judith River formation.	200–500	Beds of fresh and brackish water origin containing sandstone, sandy shale, and gypsiferous and lignitic clay.
			Claggett shale.	430–650	Dark-gray to brownish-black marine shale containing beds of bentonite and yellow calcareous concretions.
			Eagle sandstone.	120–220	Massive beds of white to buff sandstone and sandy shale; Virgelle sandstone member at base.
		Colorado shale.		1,740–2,080	Dark-blue to black marine shale containing beds of bentonite, calcareous concretions, sandy shale, and sandstone.
	Lower Cretaceous	Kootenai formation.		450–500	Nonmarine red and green shale, sandstone, and nodular limestone.
	Lower Cretaceous(?).	Morrison (?) formation.		200–300	Variegated shales, lenses of sandstone, and thin limestone beds.
	Upper Jurassic.	Ellis formation.		150–1,300	Marine sandy limestone, calcareous sandy shale, and sandstone.
Paleozoic.	Pennsylvanian.	Quadrant formation.		1,288–1,670	Beds of marine and nonmarine red and black shale, limestone, and sandstone.
	Mississippian	Madison limestone		1,950	Massive and thin-bedded marine limestone.
	Cambrian.			300	Conglomeratic limestone with flat pebbles.
				750	Mainly greenish micaceous shale.
				75	Coarse sandstone with layers of quartz conglomerate.
Proterozoic.	Algonkian (Belt series).			† 300	Dark limy shale.

* After Reeves, Frank: U. S. G. S. Bull. No. 786, p. 43, 1827.

† Thickness exposed.

continent. In western and central Europe all of the common types of sediments were laid down. In the southern portion of the continent, limestones were abundant.

Lower Cretaceous Oil.—There is little to indicate that the Lower Cretaceous was very favorable to the deposition of oil source beds although the excellence of some of the beds as reservoirs of oil is unquestioned. The Comanchean or Lower Cretaceous of the Tuxpam-Tampico embayment is without a doubt the greatest of the productive areas of this age. The oil is found in the highly fractured and water channeled upper surface of the Tamasopo limestone. It is believed to have originated in the San Felipe formation of the Upper Cretaceous, which lies immediately above the Tamasopo limestone. In the Madill pool in Marshall County, Oklahoma, production is obtained from the Trinity sand at the base of the Lower Cretaceous. The origin of the oil is not definitely known, but Hopkins, Powers, and Robinson[1] suggest that it was derived from the tilted and eroded Carboniferous strata which lie below the Trinity sand. The same horizon is believed to yield the deep oil of the Pine Island pool in northwestern Louisiana. At Luling, in Caldwell County, in southwestern Texas, the Edwards limestone of the middle of the Lower Cretaceous is an important producing horizon. The development of these horizons in Texas and Louisiana is retarded by their depth and the covering of only partly conformable strata which lie above them. As in Mexico the Lower Cretaceous beds do not appear to be of the type that can be considered as the source of the oil. They are excellent reservoirs, however.

In the Sunburst pool of Montana, some oil is produced from the base of the Kootenai formation. This is the only area in which production is being obtained from this formation. The Morrison formation in Wyoming is also the source of some oil and is believed to be of Lower Cretaceous age. The Lakota formation lying near the top of the Lower Cretaceous is an important source of oil in the same state. Oil in these beds may have been derived from beds of the same age or from those laid down in the Upper Cretaceous.

Upper Cretaceous.—The close of the Lower Cretaceous in North America was dominated by the development of the great central mountain belt of the Rocky Mountain Cordillera. The belt extended from Alaska to Central America and uplifted the whole of the western portion of the continent. From that time onward the waters of the Pacific were separated from those of the Gulf of Mexico, the Arctic, and the basinal Coloradic geosyncline which connected them. After the middle of the Upper Cretaceous, incursions of the Pacific were limited to the invasion of intermontane valleys. During the first half of the Upper Cretaceous, the trough between the coastal islands and the Central Cordillera was renewed and extended from Alaska to

---

[1] Hopkins, O. B., Powers, S., and Robinson, H. M.: U. S. G. S. Bull. 736, p. 29, 1922.

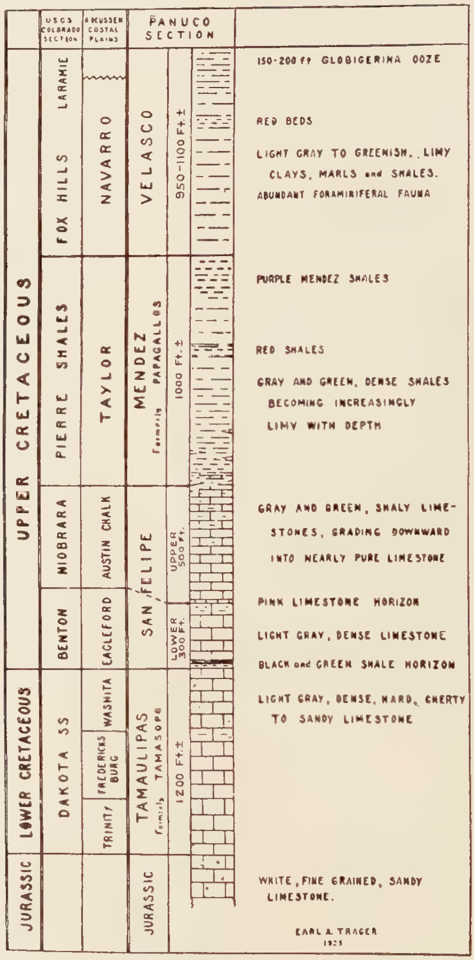


Fig. 18.—Generalized Section of the Cretaceous as present in the Panuco District of Eastern Mexico. After Trager, Earl A.: A. A. P. G. Bull., Vol. 10, p. 672, 1926.

southern California. Sandstones and shales were deposited in large amounts, and locally some conglomerates and coal beds were laid down. The area was uplifted before the end of the Cretaceous and subjected to wide-spread erosion.

The dominating event of Upper Cretaceous time in North America was the flooding of the broad Coloradic geosyncline by the waters of the Gulf of Mexico and the Arctic Ocean. This occurred early in the period when the waters formed a more or less continuous body of water from Minnesota to Utah. In the basin of the Gulf of Mexico, the eastern portion of Mexico, including Yucatan, was submerged; and the waters entered the Mississippi Valley as far north as the southern portion of Illinois.

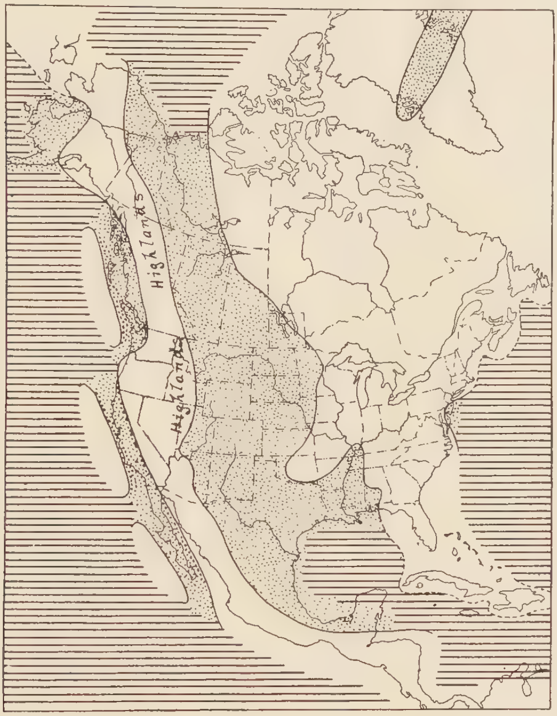


FIG. 19.—Great Rocky Mountain and Narrow Pacific Geosynclines, and Gulf of Mexico Overlap of Early Upper Cretaceous Time in North America. Shading indicates areas of greatest subsidence. After Schuchert, C.: Geol. Soc. Amer. Bull., Vol. 34, p. 228, 1923.

The deepest portion of the Coloradic syncline was that nearest the Central Cordillera. These mountains supplied the vast amount of

Table 36.—Geologic Formations of the Coastal Plains of Texas with Particular Reference to those West of the Brazos River.*

Series	Formation	Thickness in Feet	Characteristics
Recent	—	0–60	Fluviatile, flood plain, beach and dune deposits.
Pleistocene	Beaumont clay	300–900	Blue calcareous clays with nodules of lime and lenses of sand and sandy clay, terrace deposits inland.
	Lissie gravel	493–1020	Coarse gravels, inland represented by terrace deposits.
Unconformity.			
Pliocene(?)	Reynosa formation	560–1505	Limy conglomerates and limestones. Inland, upstream deposits known as the Uvalde formation.
Unconformity.			
Pliocene	Lagarta clay	346–647	Light colored or mottled pink and green clays with numerous lime nodules, stained heavily with manganese in places.
	Lapara sand	75–455	Interbedded sands and clays.
Unconformity.			
Miocene	Oakville sandstone	180–603	Gray sandstones, calcareous in part with clay lenses.
Unconformity.			
Oligocene	Catahoula sandstone	0–1200	Sandstones and clays with fossil wood.
Eocene	Frio clay	235–705	Clays with lime nodules, marls, beds of volcanic ash.
	Fayette sandstone	480–800	Sands and clays, silicified and opalized wood, lignite, and volcanic ash.
	Claiborne Group		
	Yegua formation	475–1049	Clays, shell beds, sands, lenticular lignite beds, selenite plates in clays.
	Cook Mountain formation	520–865	Greensands, greensand marks, iron ore, lignite, clay, sandstone.
	Mount Selman formation	640–820	Sands, thin seas of iron ore, lenses of lignite and clay.
Unconformity.			
Eocene	Wilcox Group		
	Carrizo sandstone	300–800	Coarse sandstones, fine micaceous sandstone.
	Unconformity		
	Indio formation	350–840	Sandstones, clays, sandy clays, lignites.
	Midway formation	260–566	Marine clays and limestones.

TABLE 36.—*Continued.*

Series	Formation		Thickness in Feet	Characteristics
Unconformity.				
Gulf or Upper Cretaceous		Navarro formation	400–500	Bluish black marls and glauconitic clays, clays with siderite and limonite, sands with calcareous concretions. West of Bexar County replaced by Escondido formation with sandstones, clays and limestones.
		Taylor Marl	475–1150	Blue calcareous clay marls. West of Bexar County replaced by the Anacacho limestone.
		Austin Chalk	276–600	Impure chalk with thin marl beds.
		Eagle Ford shale.	25–260	Laminated petroliferous shale and thin beds of arenaceous laminated limestone.
Unconformity.[†]				
Comanche or Lower Cretaceous	Washita Group	Buda limestone	0–80	Whitish or yellowish cavernous heavy bedded in upper part, thin bedded in lower part.
		Del Rio clay	30–200	Greenish-blue laminated clay, in places gypsiferous. Contains thin slabs of shell breccia and near top thin layers of arenaceous limestone.
		Georgetown limestone	15–150	Grayish marly limestone with intercalated marls and shales.
	Fredericksburg Group	Edwards limestone	250–835(?)	Hard white limestone, cavernous at some horizons. Contains many dark, irregular flint nodules in certain layers.
		Comanche Peak limestone	60 ±	Heavy-bedded white marly limestone.
		Walnut clay	25–200	Marly laminated yellow clays and thin limestones.
	Trinity Group	Glen Rose limestone	300–600	Limestone with three or more notably sandy or cavernous horizons.
		Travis Peak sand	250–300	Chiefly sand or sandstone, with bands of arenaceous limestone and conglomerate.

---

[*] Adapted from a more detailed section given by Alexander Deussen: U. S. G. S. Prof. Paper No. 126, pp. 20–23, 1924.

[†] The formations below the Eagle Ford do not outcrop in the Coastal Plain but show at the surface in the hills to the north. In the region to the northeast of the Brazos River the Eagle Ford shale rests upon the Woodbine sand but southwest of the river the Woodbine is not known.

material needed to produce the thick series of shales and sands which characterize the syncline. As the period advanced, the seas retreated with the formation of fresh and brackish water deposits and coals along the borders of the remaining seas. In the last part of the period all that remained of the syncline was a fresh water lake occupying parts of the Dakotas, Montana, and southern Saskatchewan.

The name Cretaceous is derived from creta meaning chalk. Chalk beds are of great thickness in formations of this age in France and England and have given their name to the period. Such beds were not formed in the Coloradic geosyncline, but marls and chalks are common in the Upper Cretaceous of Texas. At the base of the Upper Cretaceous beds lies a thick and prominent dark bituminous shale, the Eagle Ford formation. In eastern Mexico the lower portion of the period was largely one of lime deposition. Shales were present, however, and distinctly black types predominate in the late Upper Cretaceous. The extent of the area of submergence steadily increased throughout the period in the eastern Gulf states and on the Atlantic Coastal plain.

The Cretaceous period in North America ended with the Laramide Revolution. This caused the elevation of the Rocky Mountain Cordillera to a form not very different from that which it now has. Volcanic eruptions accompanied the rising of the mountains. A sympathetic vertical uplift of moderate extent occurred in the Appalachian area.

Cretaceous in Other Continents.—The invasion of central and southern Europe initiated during the Lower Cretaceous continued

Table 37.—Geological Formations of the Comodoro Rivadavia Area, Southern Argentina.*

Quaternary:	Tehuelchean pebble beds.
	Arucanian sandstones, clays, etc.
Tertiary:	Marine Patagonian formations (sand, clay, tuffs, etc.).
	Unconformity.
	Mammalian beds (white and greenish-yellow sandy clays).
	Unconformity.
Cretaceous:	Upper Cretaceous.
	Salamanquean (Danian) formation (greenish-red and black clays) containing upper oil horizon at the base.
	Unconformity (?).
	Senonian (gray-blue sandy clays and oil sands).
	Variegated Sandstones ("Areniscas Abigarrados").

* After Hunter, Campbell: Inst. Pet. Tech., Vol. 10, p. 833, 1924.

through the Upper Cretaceous. Limestones and chalks indicative of clear if not deep waters were widely deposited. The greater Mediterranean or Tethys, which had divided the lands of Europe and northern Asia from the lands to the south for many periods, began to decrease in size and in part to turn into an area of emergence. The uplift of this area of long continued deposition was accompanied by rapid disintegration of the continents to the south. The Late Cretaceous of southern Asia and of northern Africa was a period of tremendous black faulting and volcanic disturbance. The uplift of southern Asia and the Tethys area was accompanied by shallowing of the waters in Europe and the deposition of some oil source beds.

Upper Cretaceous Oils.—Unlike the earlier periods, production from Cretaceous horizons is not limited to North America but is obtained in considerable amount from South America and the Old World. In the Old World the Cretaceous horizons are not comparable in importance with the Tertiary beds which overlie them. In Egypt a heavy oil is taken from the top of the Nubian sandstone of the Upper Cretaceous. A part of the minor production of Italy is considered to be of this age. The deeper oil of Galicia is of Cretaceous derivation, but the greater part of the oil comes from Tertiary beds. Seepages occur in middle Cretaceous limestones in Algeria.

Less is known about the horizons of the Cretaceous in other continents, but production of oil is being obtained from them in several places in South America. In Comodoro Rivadavia unconsolidated sands yield a heavy oil. The oldest and lightest oils of Trinidad come from Cretaceous beds. Oil-bearing shales and sandstones of this age are known to extend into eastern Venezuela. These are probably closely related to those in Trinidad. The Los Infantas Pool in Colombia produces from Eocene sandstones, but they overlie a series of Upper Cretaceous shales and limestones. These are bituminous in character and are considered by some to be the source of the oil. In Mexico, while the main producing horizon is the Comanchean limestone, the San Felipe shales and limes of the Upper Cretaceous not infrequently produce on a large scale. This is particularly true where the shales are fractured and fissured. The shales are undoubtedly the source beds of the oils which are found below them.

Production from the Cretaceous is wide-spread in the United States. The deepest producing horizon at Coalinga in the Valley Field of California is of Cretaceous age. It is not an important horizon compared with the Tertiary beds, however. Cretaceous beds form the most important producing horizons of the Rocky Mountains. They yield oil and gas in the San Juan Basin in northwestern New Mexico, at several points in Colorado, eastern Utah, and Montana, and are the source of the bulk of the oil produced in Wyoming. The Colorado formation, which contains some of the most important oil horizons and overlies others, embraces several dark shale beds from which the oil undoubtedly was derived.

With the exception of small amounts of oil now being taken from the Lower Cretaceous and the Eocene, all of the oil and gas produced in northern Louisiana, southern Arkansas, and the Stratum belt of Texas, comes from beds of Upper Cretaceous age. The series also contains suitable source beds.

The Mesozoic as an Oil-yielding Era.—The conditions underlying the deposition of the oil-bearing sediments of the two Cretaceous periods bear many points of resemblance to those existing during Paleozoic deposition in the Eastern and Mid-Continent areas. In the eastern half of the Coloradic Sea, broad open waters were probably in existence, but the previous history of the mountain building movements in the western half leads to the conclusion that deposition was carried on in a series of more or less connected basins of relatively limited individual extent. Between the emergent islands, sediments which were at least in part derived from their erosion, were deposited. Thus, while in a general way the formations within one of these basins conform with those of the others, the exact position of the source beds and reservoir rocks is not the same. The non-existence of later mountain building movements is not suggested, but the importance of previous topography upon the manner of deposition should be stressed. In the uplifts and crustal movements following the deposition of Cretaceous beds, the centers of crustal movement would probably be those which had been centers of previous uplift. The synclines, from around whose rims the bulk of the oil has come up to the present, are in part synclines resulting from post depositional uplifts, and in part from the form which they had during the period of deposition.

Except in unusual cases, the Cretaceous strata throughout the world have not been subject to dynamic metamorphism to the same extent that the Paleozoic or even the early Mesozoic have. In the search for oil it is not necessary to limit the areas of search to zones of broad gentle folds to the extent that is necessary in the Paleozoic.

The importance of the Cretaceous as an oil producing horizon contrasts strongly with the small yield of the Triassic and Jurassic. In

Europe the small amount of oil in the Jurassic may be considered as due in part to escape from highly contorted and fractured beds. In North America and possibly in other continents the scarcity of oil seems to indicate the existence of conditions unfavorable to the deposition of source beds.

Cenozoic Conditions.—While the length of the Cenozoic was considerably less than that of any of the eras which preceded it, its present importance as an oil producer is greater than any one of them. It has been divided into the following divisions: Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene and Recent. This extensive division of a time interval of comparatively short duration, and the use of division names, which are at best only of continental application, is not entirely satisfactory. The term Paleocene has very largely been given up, and its deposits considered as the basal portion of the Eocene. The United States Geological Survey considers the calling

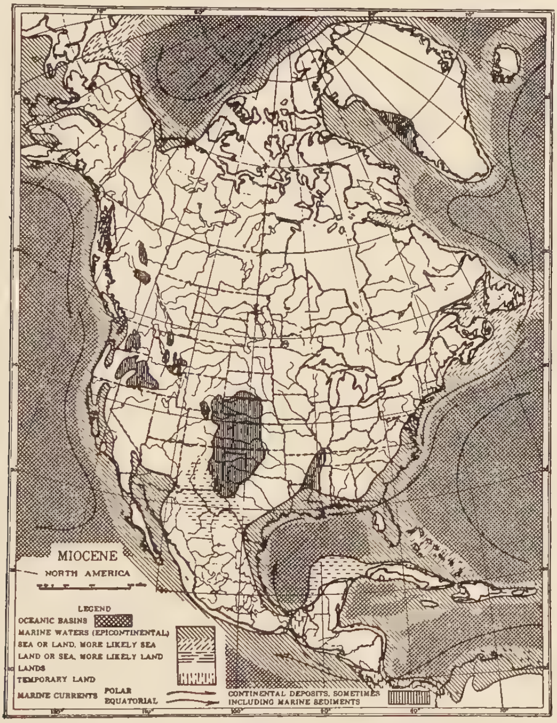

MIOCENE
NORTH AMERICA
LEGEND
OCEANIC BASINS
MARINE WATERS (EPICONTINENTAL)
SEA OR LAND, MORE LIKELY SEA
LAND OR SEA, MORE LIKELY LAND
LANDS
TEMPORARY LAND
MARINE CURRENTS
POLAR
EQUATORIAL
CONTINENTAL DEPOSITS, SOMETIMES INCLUDING MARINE SEDIMENTS

Fig. 20.—Paleogeographic Map of North America during the Miocene. After Miller, W. T., adapted from Willis, Bailey: Historical Geology, p. 295, 1916.

of the divisions, Eocene, Oligocene, Miocene, and Pliocene epochs as justified, and their grouping together as the Tertiary period as advisable. Pleistocene and Recent are handled in the same way, becoming epochs in the Quarternary period. There is also wide-spread use of the divisions upper and lower, or early and late Tertiary. The latter usually includes the Miocene and the Pliocene and is frequently called the Neogene. The early Tertiary includes the Oligocene and Eocene and is referred to as the Eocene, Paleogene, and Nummulithic as well as early Tertiary.

North American Tertiary.—The coast of North America had much of its present form during the whole of the Tertiary. In the Eocene epoch, the Pacific waters invaded the Valley of California, lying between the Coast Ranges and the Sierra Nevadas. They also formed an epicontinental shelf sea in the area of Puget Sound. There was a similar overlap of the Gulf of Mexico and the Atlantic Ocean upon the low-lying coastal areas of Yucatan, eastern Mexico, the Gulf states, and the Atlantic states from New Jersey southward. In California, the Eocene was largely a period of sandstone and conglomerate formation, but in the Gulf area sandstones alternated with shales. Some were of dark color, some were of fresh water character and contained lignites, and others were of marine character with no evidence of organic matter in them. In the Great Plains of the western states, great bodies of continental deposits of lake and piedmont character were laid down. Except as they formed porous reservoir rocks in which oil might accumulate, they were not generally favorable to the accumulation of oil. In western Wyoming, western Colorado, and Utah, the Green River kerogen or oil shales were laid down in a body of fresh or only slightly salty water. Whether it was a body of water lying at sea level and connected to the sea by a comparatively long and narrow strait, or an elevated basin with a flowing outlet, is not known. The conditions of deposition of the shales were probably somewhat different from those surrounding the deposition of black shales in earlier periods.

The record of the Oligocene in North America is, with the exception of the area of the West Indies, largely one of emergence and retrogression of the ocean waters. If Oligocene strata were deposited in California, they were restricted to sands and boulders. In the Gulf states shallow water sands and clays are found interbedded with one another.

The Miocene of the Gulf area was largely a continuation of the

Oligocene. Deposition was restricted to the southern Gulf and southeastern Atlantic coastal states. Mexico and the West Indies were above the water line throughout most of the epoch. While there was no more marked horizontal extension of the seas upon the continent in the Miocene than in the earlier epochs, this time was one of tremendous subsidence in the depositional areas in southern California and the region of the Gulf of California. In the first area a thick series of sands and conglomeratic material was deposited. This was followed by the deposition of thick beds of diatomaceous shales, known commonly as the Monterey shales but having several local names.

TABLE 38.—GENERALIZED STRATIGRAPHIC COLUMN OF ROCKS IN THE LOS ANGELES BASIN, CALIFORNIA.*

Geologic Age	Formation		Thickness	Lithology
Recent				Alluvium and terrace materials.
				Unconformity
Pleistocene	San Pedro group		500±	Sands and gravels (partly marine).
				Unconformity
Pliocene	Fernando group	Saugus formation	1,400±	Conglomerates, sands, and blue clays (partly marine).
				Unconformity
		Pico formation	5,600±	Sands and blue, brown and gray sandy shales. Locally conglomeratic (chiefly marine).
				Unconformity
Miocene	Monterey group	Puente formation	3,200±	Diatomaceous shales with local sandstones and thin, brittle, calcareous layers (marine).—Intrusive basalt and diabase. —Heavy-bedded sandstones with interbedded sandy, siliceous, and diatomaceous shales, and locally a basal argillaceous lens (marine).
Oligocene (?)		Vaqueros formation	1,000+	Coarse, massive sandstones; locally conglomeratic (chiefly marine).
				Unconformity
Pre-Cretaceous				Dark, micaceous schist intruded by granite.

* After Eaton, J. E.: A. A. P. G. Bull., Vol. 10, p. 755, 1926.

During Pliocene time California was elevated above sea level. Lower California, however, remained below the level of the water. The coastal plain around the Gulf of Mexico was partly covered with water from the vicinity of Yucatan to Alabama.

The Tertiary in Other Continents.—While there is reason to believe that Tertiary history in South America resembled that of North America in restriction of waters to basinal areas in close proximity to the coast, such was not the case in Europe, Asia, and Oceania. In these areas submergence began on a large scale early in the period. Much of southern and eastern Europe was submerged. The seas were not confined to that continent but spread northeastward into Asia to join with the Arctic and eastward as far as northern India. The Lower Tertiary is widely known as the Nummulithic, because of the great thickness of limestone deposits formed from the shells of nummulites, a species of foraminifera. Previous to this, wide areas

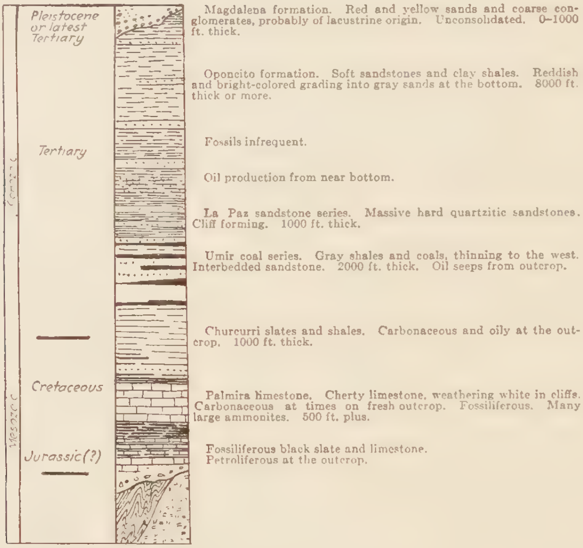

Pleistocene or latest Tertiary
Tertiary
Cretaceous
Jurassic(?)
Cenozoic
Mesozoic
Magdalena formation. Red and yellow sands and coarse conglomerates, probably of lacustrine origin. Unconsolidated. 0–1000 ft. thick.
Oponcito formation. Soft sandstones and clay shales. Reddish and bright-colored grading into gray sands at the bottom. 8000 ft. thick or more.
Fossils infrequent.
Oil production from near bottom.
La Paz sandstone series. Massive hard quartzitic sandstones. Cliff forming. 1000 ft. thick.
Umir coal series. Gray shales and coals, thinning to the west. Interbedded sandstone. 2000 ft. thick. Oil seeps from outcrop.
Churcurri slates and shales. Carbonaceous and oily at the outcrop. 1000 ft. thick.
Palmira limestone. Cherty limestone, weathering white in cliffs. Carbonaceous at times on fresh outcrop. Fossiliferous. Many large ammonites. 500 ft. plus.
Fossiliferous black slate and limestone. Petroliferous at the outcrop.

Fig. 21.—Generalized Stratigraphic Section in the Eastern Magdalena Valley of Colombia, between the Carare and Sagamosa Rivers. After Huntley, L. G., and Mason, Shirley: A. I. M. E. Trans., Vol. LXVIII, p. 1017, 1923.

had been carried below the surface of the ocean to form island dotted seas in the East Indies, the Philippines and the Japanese Archipelago. Reemergence, especially in the East Indies, probably began during the early parts of the Tertiary. The uplifted areas formed the source of the sediments which were laid down in the later parts of the period. The uplifts were characterized by intense folding, faulting, and volcanic activity.

In Europe, the Oligocene epoch was one of rapid shallowing and shrinkage of seas, especially in the western and northern areas. In southern Europe uplift was not so evident; but the development of Carpathian, Balkan, and Caucasus ranges, occurred partly at this time. Oligocene mountain building was apparently prominent in southern Asia also. The wide-spread orogenic movements of the epoch must be considered as of major importance in the shallowing of waters and preparing the way for the deposition of the source beds of petroleum which were laid down over wide areas during the Miocene.

Except for the fact that its areas of deposition were, like those of the Cretaceous in North America, interrupted by numerous islands of recent uplift, the extent of the Miocene of the Old World was approximately that of the Eocene. The sediments, however, were en-

Table 39.—Generalized Geologic Section in Venezuela.*

Age and Thickness in Feet	Formation	Character at Type Locality
Quaternary 300 ±	Llanos formation	Massive, poorly sorted, soft, colored, coarse sandstones and mottled white clays. Much iron oxide. Flat lying. Type locality, southern Monagas and Anzoategui.
Unconformity.		
Pliocene 1000 ±	Maracaibo formation	Massive, cross bedded, poorly sorted sands and clays, much iron oxide. Type locality, around Maracaibo City, Zulia.
Unconformity.		
Miocene 8000 ±	Arimpia formation	Alternating massive, brown and red, coarse, soft sandstones and white to brown clays, ferruginous. Lower part, clays more shaly and sandstones more laminated. Brown, sandy shales. Type locality, southwestern Perija, State of Zulia.
	Las Lajas formation	Fairly hard, well-bedded, calcareous, ferruginous, brown sandstones, dark brown, sandy shales, dark brown shales, thin beds lignite and bituminous coal. Type locality, Las Lajas, State of Falcon.
Unconformity.		
Oligocene 5000 ±	Rio Raya shale	Dark gray and brown shales, limonite and pyrite concretions, conchoidal fracture. Type locality, Raya River in Northeastern District of Sucre, State of Zulia.
	Churugarita limestone	Massive gray formaniferal limestone. Type locality South Central Miranda, Zulia.

Table 39.—*Continued.*

Age and Thickness in Feet	Formation	Character at Type Locality
Minor unconformity.		
Eocene 4750 ±	Bocorron sandstone	Massive, coarse, conglomeratic, white to brown fairly hard sandstone. Some shale at bottom. Type locality, Bocorron, State of Trujillo.
	La Rosa coal measures	Alternating beds of fairly hard, coarse, massive, brown sandstone; brown sandy shales and brown to black shale. Thick bituminous coal beds. Type locality, La Rosa coal mines, western Mara and Paez, State of Zulia.
	Rio Guasare formation	Alternating beds of hard brown sandstone, black slaty shales and thin, hard brown, fossiliferous limestones.
Unconformity.		
Cretaceous 6000 +	Guanoco shale	Dark gray to black, fossiliferous limy shale. Type locality, Guanoco, State of Sucre.
	Guacharo limestone	Massive gray crystalline, fossiliferous limestone. Type locality, Guacharo, State of Monagas.
	Punceres sandstone	Lower part massive, dark brown to red, coarse hard sandstone. Upper part alternating beds of same sandstone with black shale and dark gray limestone. Type locality, Punceres, State of Monagas.

* Adapted from Garner, A. Hamilton: Suggested Nomenclature and Correlation of the Geological Formations in Venezuela, Pet. Dev. and Tech. in 1925, pp. 677–684.

tirely different, shales and sandstones replacing the Nummulithic limestones. Among the shales in all of the producing areas are beds having the characteristics of petroleum source beds.

Late Miocene brought the deposition of such beds to a close in practically all of the areas in which they were laid down. It was a period of marked uplift in the Alps, the Caucasus, the Himalayas, and other mountain systems of southern Europe and Asia. In the Far East island areas deposition continued much longer.

Tertiary Oil.—A limited amount of oil is obtained in California and Wyoming from strata which are considered to be of Eocene age. Some oil is obtained in the Eocene of southwestern Texas. In Italy

TABLE 40.—GEOLOGIC SECTION—SOUTHWEST PERSIA.*

	Recent Deposits—High gravels, silts, and alluvial fans.
Pliocene:	Bakhtiari Series—Massive conglomerates, loose sands and clays, maximum thickness up to 15,000 feet.
Miocene:	Fars Series—Upper—Thick calcareous sandstones, red marls, and shales, and a little veined gypsum, several thousand feet in thickness.
	Lower—Sandy detrital limestones, calcareous sandstones, blue and red shales, and occasional beds of gypsum. Varies from a few hundred feet to more than 2500 feet in thickness.
	Lower—Bedded gypsum with intercalated red and blue shales and marls, salt, anhydrite, and occasional beds of detrital and secondary limestones. Varies from relatively thin beds up to 5000 feet or more.
Oligocene:	Asmari Limestone Series—Massive to thickly bedded, hard, compact, brown or gray brown, formaniferal limestone containing porous dolomitic sections in the upper part, locally some gypsum, and hard calcareous shales near base. Up to 2200 feet in thickness. The porous dolomitic section is the chief oil container.
Eocene:	Spatangid Shales—Bluish green splintery shales containing beds of fine grained argillaceous limestone. 250 feet, approximate.
	Upper Thin Bedded Limestones—Thin bedded limestones with shale bands, up to 1600 feet thick.
Eo-Cretaceous:	Blue and Purple Shales—Non-fossiliferous shales, 1200 feet thick.
Cretaceous:	Lower Thin Bedded Limestones—Limestones intercalated with fissile purplish blue shales toward summit, up to 1200 feet.
	Dash-i. Gul or Siah Kuh Limestone—Massive limestones.

* Mainly after Richardson, R. K.: The Geology and Oil Measures of Southwest Persia, Inst. Pet. Tech. Jour., Vol. 10, pp. 256–296, 1924.

it is a minor source of production. It forms an important horizon in Galicia. The production of Peru and some of the oil from Colombia is considered to be of this epoch. Some of the wells in the Isthmuthian area of Mexico tap horizons of Eocene age.

The Oligocene is productive in a small way in California and Wyoming. Some of the seepages and non-commercial wells in Colombia show oil in strata of this age. It is a substantial producer in Texas and Louisiana. It is of major importance as an oil horizon in parts of Galicia, Roumania, and Russia.

Pliocene is an epoch of little importance as a producer of oil. While it has been identified as a producing horizon in California, the Gulf area of Texas, Trinidad, Italy, Roumania, and Sumatra, it is of much less importance than the beds that lie below it. These are generally of Miocene age. Miocene strata are largely shales and sands, the latter being the oil containing beds. Such beds yield the bulk of the oil in California, Venezuela, Trinidad, Barbadoes, Roumania, southeastern Russia, Burma, Japan, and the East Indies. They are important sources of oil in southern Texas and Louisiana, Galicia, and Egypt. In Persia, the oil, while of Miocene origin, is obtained from underlying porous limestones instead of sands.

Table 41.—Section of Apsheron Peninsula, Russia.*

Stage		Formation	Thickness Meters	Lithological Character
Post Pliocene	Upper	Coastal deposits of present Caspian extending to 10 m. above present sea-level.	5–10	Sands, clay, and shell fragments.
		Older Caspian deposits forming conglomerates at a height of 12 and 26 m. and reaching to a height of 34 m. above present sea-level.	14	Sands, clays, boulders and shell conglomerates.
		Aralo-Caspian Terraces at a height of 96 and 186.5 m. (beds not disturbed).	3–6	Limestones, sands with boulders and conglomerates.
	Middle	Bakunian (disturbed).	46	Limestones, sandstones, sands, clays and conglomerates.
Pliocene		Apsheronian.	453	Limestones, boulder limestones, oolites, shell beds, sandy limestones, calcareous sandstones, sands, marls, sandy clays, and clays; limestones predominate in the upper beds, sands in the middle, and clays in the lower; the thick clay series (110 m.) contain layers of tufaceous sands at base.
	Lower	Pontian (?).	76	Dark colored clays interbedded with sand and marl; contain gas at Bibi-Eibat.
		Transition beds.	11.3	Dark clays with interbedded gas sands; sands gas bearing at Bibi-Eibat.

TABLE 41.—*Continued.*

Stage		Formation	Thickness Meters	Lithological Character
Miocene	Upper	Akchagylian.	49.4	Dark colored clay shales and shaley clays interbedded with limestones and white tufaceous sands; the sands are gas and oil containing in Bibi-Eibat.
		Fresh water formation.	490	Clays, sandy clays, sands with clay and sand; clays predominate.
	Middle?	Unfossiliferous series:		
		First series, sand oil bearing at Bibi-Eibat.	434	Sandy clay series; sands predominate.
		Second series, sand oil bearing in Yasmal Valley.	185	Sands and sandstone with interbedded clays.
		Break in the series until the Spirialis beds.		
	Lower	Spirialis beds.	98	Siliceous, calcareous and sandy clay rocks with interbedded ferruginous sandstones; in places oil bearing.
		Cedroxylon beds.		Dark colored, laminated shales with concretions of siliceous sandy rocks.
Oligocene?		Amphisyle beds.		Shales, dark, and chocolate colored, weathering yellow.
		Lamna beds.		Green, sandy clay shales with interbedded siliceous sandy rocks and white marls; oil bearing in places.

---

* After Golubiatnikov as given by Thompson, Beeby and Madgwick, T. G.: A. I. M. E. Trans., Vol. LXV, pp. 22–23, 1921.

Quaternary Horizons.—While Quaternary deposits are common in many parts of the world, they are rarely containers of oil. Their extreme youth and highly unconsolidated and unaltered character are not favorable to the formation of oil from the source materials which might have been deposited. Further limitations are raised because of the conditions under which they were deposited. Pleistocene is better known as the Glacial period. Its deposits, covering all of the northern portions of North America, Europe, and Asia, reflect that condition. In unglaciated areas Pleistocene deposits are usually continental in character; that is, made up largely of piedmont, fresh water, lake, arid basin, fluviatile, and delta deposits. Where deposits were laid down along the coast, they were largely laid down in oscillating seas in which periods of emergence have brought aerial decay and leaching of the organic matter. If they contain oil today, it is probable that the oil came from lower horizons.

Tertiary as a Container of Oil.—The outstanding characteristic of the basinal areas in which Tertiary oils are found is their close conformity with present topographic forms. Except in the Near East the producing areas are found in basins that are immediately tributary to the oceans. In that area the basins in which the oil is found are closely related to arms of the sea still in existence. The differences between the producing beds and those of earlier age are marked.

Limestones are not commonly the containers of oil. This is characteristic of near shore deposition in small but marked basinal troughs. Because of their age, the beds are largely unconsolidated. Oils are commonly of low grade. The productive areas are characterized by folds of major size and are associated with large faults. Seepages are common, but the loss of oil through seepage has not reached such proportions as to destroy the value of the rocks as oil containers, as it has in similarly folded and faulted rocks of Jurassic age. Surface waters entering the oil containing horizons have caused greater alteration than in the oils of older ages. The position of the oil and gas in rocks of the Tertiary in most of the productive areas suggests that they would not have been preserved through future geologic time as the Paleozoic oils have been in the past.

A SELECTED BIBLIOGRAPHY ON REGIONAL AND HISTORICAL GEOLOGY WITH SPECIAL REFERENCE TO NORTH AMERICA.

1. Blackwelder, Eliot, United States of America (Part of Handbook of Regional Geology, edited by Steinman and Wilckens).
2. Chamberlin, T. C., and Salisbury, R. D., Geology, Volumes II and III, Earth History.
3. Grabau, A. W., Textbook of Geology: Part II, Historical Geology.
4. Miller, W. J., Introduction to Historical Geology.
5. Pirsson, L. V., and Schuchert, Charles, Textbook of Geology, Part II, Historical Geology.
6. Schuchert, Charles, Sites and Nature of the North American Geosynclines, Geol. Soc. of America, Bull. 34, p. 151–230, 1921.
7. Willis, Bailey, Index to the Stratigraphy of North America, U. S. Geol. Survey, Prof. Paper 71, 1912.
8. Willis, Bailey, Paleogeographic Maps of North America, Jour. of Geol., Vol. 17, 1909.
9. Willis, Bailey and Salisbury, R. D., Outlines of Geologic History with Especial Reference to North America.

CHAPTER VII.

PETROLEUM RESERVOIR ROCKS.

The existence of rocks suitable to perform the function of storing the oil and gas is only slightly less important to the accumulation of petroleum than the presence of suitable source beds. The existence of the reservoir is determined partly by the physical properties of the rocks themselves and partly by the attitude or inclination of the rocks. The latter will be considered in later chapters.

Containers and Retainers.—The rock may be considered as performing one of two functions, retaining or containing. The container rock is a highly porous type in which the interstices are such as permit the oil, gas, and water, to move freely. It is an ideal medium in which the assorting and separation of these substances may take place, but is not in itself capable of retaining oil or gas. Although less frequently mentioned, the dense non-porous retainer rocks, which prevent the escape of oil, gas, and water from the container rocks, are no less important.

The division of rocks into container and retainer types depends solely upon their porosities. The porosity of a rock may be defined as the property of containing interstices. or openings. Such openings may vary in size from caverns down to subcapillary pores. The expression ''high porosity'' usually indicates an abundance of openings, but ''low porosity'' may not indicate the absence of pore spaces as much as the lack of openings of sufficient size to permit the storage of oil, and later, the extraction of the oil from those openings.

According to G. F. Becker,[1] the interstitial pore space in a sandstone made up of closely packed spherical grains is equal to 25.96% of its total volume. C. S. Schlicter [2] has pointed out that porosity is not affected by the size of the grains. Thus the porosity of a gravel which is composed entirely of perfect spheres, each two millimeters in diameter, is the same as that of a silt or clay made of perfect spheres, having a grain diameter of 0.05 millimeters. They are not, however, of the same porosity as judged from the practical standpoint of the oil producer, the first being an excellent container, and the second an

[1] Mon. U. S. G. S., Vol. 13, p. 399, 1888.

[2] U. S. G. S., 19th Annual Report, pt. 2, pp. 305–328, 1899.

effective retainer. Such differences can be shown experimentally to depend upon the classification of the rock openings, whether supercapillary, capillary, or subcapillary. In rocks having large openings the movement of water and oil is much like that in water mains, pipes, and sewers. It is controlled entirely by gravity. According to Daniell[1] capillary forces become effective when the diameter of the tube through which the water is flowing is reduced to about $\frac{1}{15}$ of an inch or 0.5 millimeters. This is considered low by later investigators but is indicative of the fact that capillarity is an important force in determining the movement of liquids in most oil field container rocks. For sheet openings the limits are considered to be equal to one half of those for tubular openings.

Capillary Openings.—In capillary openings the molecular attraction of the wall of the grain of sand exerts a definite pull upon the water or the oil molecule. This is known as the quality of adhesion. The cohesive attraction of the water molecules for one another is sufficient to hold them to the molecules that are attracted by the sand grains. Liquids are unable to circulate through rocks in which the openings are of such types as make these forces comparable with gravity in strength. Differences between adhesive and cohesive properties of waters and oils have already been pointed out. The lower surface tension of oil makes it amenable to gravitational forces to a greater degree than water is. Unless unaccompanied by water, oil is found only in the portions of the capillary containers having the largest openings. Water then enters the smaller pores. Circulation through capillary openings demands a force greater than that of capillarity. The gravitational force must be considerably greater than that of capillarity. Such movement may be accomplished much more readily when liquids are hot than when they are cold. Gases are not affected by capillary attraction except as their exclusion from pore spaces is accomplished by the entrance of liquids which function under capillary laws.

Less is known about conditions in extremely fine openings. Below the capillary interstices are openings so small that the attraction of their walls extends through the whole of the space between them. Retention is dependent solely upon the adhesive properties of the wall substance. Water or, in fact, any liquid entering such interstices is so firmly held by the force of adhesion that it cannot be moved except by pressures unknown in shallow formations, or by conversion

[1] Daniell, Alfred: A Textbook of the Principles of Physics, 2d ed., p. 293.

of the liquid into a gas by heat. According to Van Hise[1] subcapillary openings include all interstices of less than 0.0002 millimeters diameter in the case of tubular openings and 0.0001 millimeter for sheet openings. More recent studies have tended to indicate that capillary action is capable of extension to even lower limits. However, movement in such extremely fine openings is probably extremely slow if accomplished at all. Such movement does not appear possible except under abnormal pressures and temperatures.

While Schlicter demonstrated that the porosity of masses composed of perfect spheres is independent of the size of the spheres, this is true only when the diameters of all of the spheres in the respective samples tested are alike. It does not mean that the pore space of rocks composed of spherical bodies of various sizes will equal that of the theoretical type. The pore space in such cases may be above or below the theoretical 25.96%, according to the proportions of the grains of varying sizes present.

Origin of Openings.—If we consider porosity to include not only pore spaces of minute character but all openings, we must include cracks, fissures, and cavernous openings. Openings of both large and small size may be classified according to their origin into primary and secondary types. The first would include all types that were formed at the time the sediments or other rocks were deposited. The second would include all those that were formed as a result of alteration of the rocks derived from those sediments. The causes of variation in pore space under these two main headings are as follows:

Primary causes of porosity:

1. Shape of constituent particles.
2. Assortment of constituent particles.
3. Arrangement of particles.
4. Degree of cementing during deposition.

Secondary causes of porosity:

1. Degree of compacting.
2. Introduction of cementing matter.
3. Solutional action of percolating waters.
4. Shrinkage crack formation.
5. Openings resulting from recrystallization.
6. Openings resulting from stresses due to crustal action.
7. Openings resulting from surface weathering.

---

[1] A Treatise on Metamorphism, U. S. G. S. Mon. 47, pp. 134–146.

Shape of Particles.—Unlike the perfect soil the grains of sedimentary deposits are of varying shape. The sand of the beach deposit may be well rounded, but that of the piedmont or river area is usually angular. Clay particles, being largely of kaolin, are frequently flat. Sand grains, though more or less smoothed off, are seldom perfect spheres. One dimension is normally greater than the others. Deposits of carbonate of lime frequently retain the form of the shell from which they were derived. Shell bodies may be nearly round in some cases and in others have the general form of a pencil. The greater the angularity, the more ornate and irregular the form, the greater the removal of the form from block-like or flat character, the greater will be the porosity resulting.

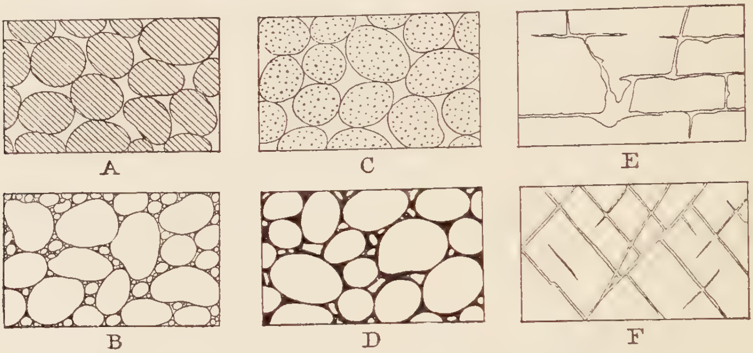


Fig. 22.—Diagram showing several types of rock interstices and the relation of rock texture to porosity. A, Well-sorted sedimentary deposit having high porosity; B, poorly sorted sedimentary deposit having low porosity; C, well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity; D, well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; E, rock rendered porous by solution; F, rock rendered porous by fracturing. After Meinzer, O. E.: U. S. G. S. Water Supply Paper, 489, p. 3., 1923.

Pebbles are the products of the disintegration of earlier rocks. Thus they inherit the characteristics of those rocks. If these rocks were highly porous, the pebbles are likely to be also. In considering the shape of particles it is necessary to make allowance for their internal structure.

Assortment and Arrangement.—In general the deposit in which all of the grains are of approximately the same size has the greatest porosity. Small grains materially reduce the pore space of conglomeratic or pebbly deposits by filling in the spaces between the large pebbles. Where the assortment contains grains of irregular form as well as different size, this tendency may be neutralized. Arrangement is also important. Settling in gravel, sand, and coal piles is largely traceable to rearrangement so that individual grains wedge into each other more closely. Heaped deposits, such as those of the delta, the glacial moraine, and the piedmont slope are generally of high porosity compared with the more fully assorted and arranged deposits of the beach or open sea.

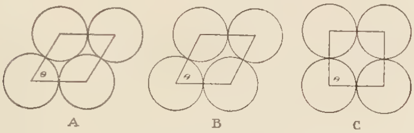


Fig. 23.—Section of four contiguous spheres of equal size. A, Most compact arrangement; B, less compact arrangement; C, least compact arrangement.

Simultaneous Cementing.—The introduction of cement into sedimentary rocks is frequently considered as taking place at a time later than their deposition as sediments. Probably this is true in the case of the majority of sandstones. Yet in some, deposition and cement introduction must have occurred at the same time. The gypsum that is precipitated simultaneously with sand and silt in the rapidly evaporating waters of a final basin can hardly avoid lodging between the grains and cementing them together. Much of the silica and certainly the bulk of the argillaceous matter, which form the cementing substance of many sandstones of marine and delta origin, must have been precipitated from the colloidal state at the same time as the sand grains were laid down. Cementation in limestones cannot have lagged much behind deposition because of the ease with which calcium carbonate is redissolved and reprecipitated. Similar action may be considered as having occurred where sandstones having a lime cement are found.

Later Cementing.—The greater part of the cement present in sedimentary rocks of the sandstone type is considered to have been introduced by percolating waters after the deposit had been covered to some extent. The cements introduced in this way include silica, calcium carbonate, and hydroxides of iron. There is a wide range in the amount of cement contained in the interstitial spaces of rocks even though they are of the same age and general character in other respects.

In general the older rocks contain considerably more cement than the younger ones. However, highly cemented sections are not unusual in rocks of Tertiary age, and soft uncemented ones are common even in the Paleozoic horizons. It need hardly be stated that the pore space decreases directly as the amount of cement present increases. Effective porosity is materially lessened by cementing. Cement may be distributed unevenly through the porous rocks. In such cases the cement may be so distributed as to give the impression that the whole of the rock is lacking in porosity. It is not unusual for wells, drilled in otherwise structurally ideal areas and surrounded by producing wells, to strike cement-filled pore spaces and fail to obtain commercially recoverable amounts of oil.

Compacting.—The pore space of many soils is as high as 50%. This is largely due to lack of compactness and because many of the individual grains are found to be aggregates containing pore spaces within themselves. It is not unusual for clays to contain 40% of pore space. However, a considerable proportion of that pore space is of subcapillary size and its water or other liquid content not recoverable except under conditions not present in oil fields. Shales and slates, the lithified and metamorphosed products respectively of the alteration of clays, are known as rocks of low porosity. They are especially lacking in pores larger than those of the subcapillary type. The explanation of this, which appears most logical, is that the flat kaolin particles have rearranged themselves to occupy less space than they originally did, and that, in the process of rearrangement, the flat particles have been placed side by side and the larger spaces practically eliminated.

The conversion of chalks and soft marls into limestones of high density may be considered as having been accomplished in much the same manner. Here part of the reduction in the pore space may be traced to solution and redeposition as well.

Solution Openings.—While solution with immediate redeposition or deposition from a saturated solution entering the pore spaces of a rock are responsible for decrease in porosity, solution may also cause increase of the porosity of the rock as a whole. Water is constantly moving through the upper sections of the earth's crust. Its pathway is determined by the existence of previous openings in the rocks. Fissures, joints, and bedding planes form the only openings suitable for such movement through dense and impervious shales and limestones. Unless the water be saturated and devoid of carbon dioxide, the calcium carbonate of the openings in the limestone will be dissolved and the openings considerably enlarged.

This constant leaching action, if continued for a sufficient time, may result in formation of a honey-combed rock containing openings up to the size of caverns. Such solvent action is developed best above the level of the water table; but, as the water level of a previous geologic period may not be that of the present, solution cavities may be found at considerable depth. Their large size and intercommunication make possible the concentration of oil by gravity to a much greater extent than is common in the finer openings. Recovery is much more rapid also.

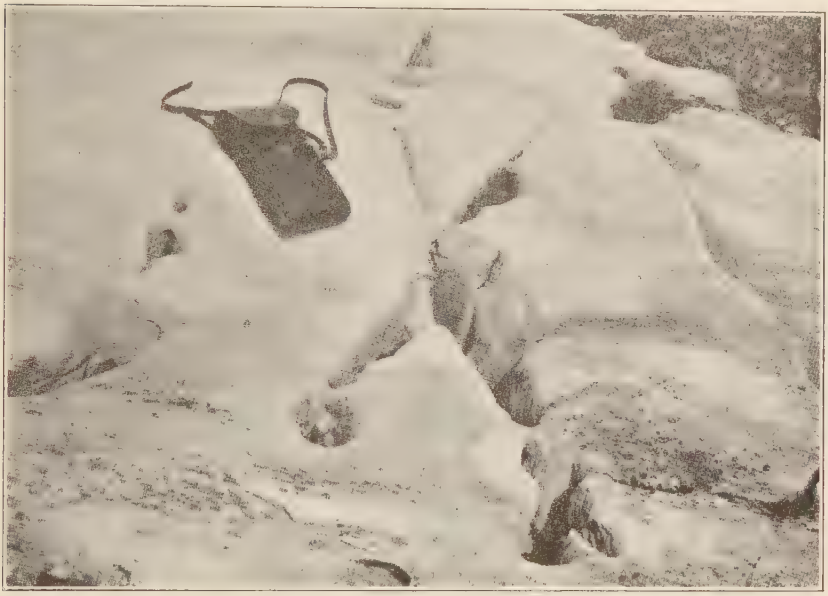


FIG. 24.—Limestone surface, showing solution channels along joints. Photograph by A. J. Ellis, U. S. G. S. Water Supply Paper 489, plate VII, 1923.

Recrystallization.—The process of dolomitization is closely allied to this. The increase in pore space in many limestones is at least partly due to this action. Dolomitization is a process of substitution of magnesium for part of the calcium contained in the original calcite of the limestone to form the calcium magnesium carbonate, known as dolomite. The volume of the rock shrinks to the extent of about 12% if no addition is made during the process. If, as apparently is most commonly the case, the substitution is carried out before lithification has taken place, there is no reason to expect that the porosity of the limestone of dolomitic character will be materially different from that of the pure calcite type. In some cases dolomitization occurs at a time subsequent to lithification. In these the development of joints and shrinkage cracks may be anticipated. Similar results may occur during the period of dehydration; but as dehydration is largely accomplished at the same time as lithification, it is probable that comparatively little pore space is developed. Shrinkage in volume through cooling is of major importance in igneous rocks and those that have been subjected to the heat of contact metamorphism.

Openings may result indirectly from the force exerted by growing crystals upon the walls of openings that contain them. In some cases it is probable that the force exerted has been sufficient to widen greatly the cracks through which solutions gained entrance. While a possible explanation of the conditions in some mineral veins, it does not appear that the joints and cracks known in oil fields are of this origin. In fact, the crystals of calcite and other substances which occur in shale cracks may more logically be considered as filling preexisting open cracks rather than as the cause of them.

Crustal Movements.—When unconsolidated sediments are subjected to dynamic pressure, they tend to flow in such manner as to relieve that pressure. As long as they remain plastic, flow is accomplished without difficulty. But when the sediment becomes a rock and attains rigidity, flowage is no longer possible except under extreme pressures. Relief may come through faulting of the strata. In this, one portion moves with respect to the other. More commonly the strain is taken up by folding of the rocks or by movement within the rock beds. In rocks that are heterogeneous in character, that is, composed of pebbles of irregular size and shape held together by cement, the adjustment is frequently made by the slipping of component units. In sandstones, the action is much the same. In limestones, there is an early development of hardness and rigidity, which, together with the homogeneity of the mass, make it amenable to breakage along planes that cut the rock with definite knife-like surfaces. Such breaks are limited to one bed in most cases and are known as joints.

While shales and clays are homogeneous, they normally lack the rigidity necessary for the development of joints. Where shales have become slaty in character, the development of joints is not unusual.

Joints may materially increase the porosity of rocks. Their volume is normally small compared with the total volume of the rock which contains them. Their greatest importance probably lies in the fact that, together with bedding planes, they form ideal passages for the circulation of waters capable of dissolving matter contained in the rocks. The jointed limestone may develop a high porosity in that manner. As the jointed slate-shale is composed mainly of insoluble material, its porosity is not increased to any great extent by solution and remains equal to the volume of the joints themselves.

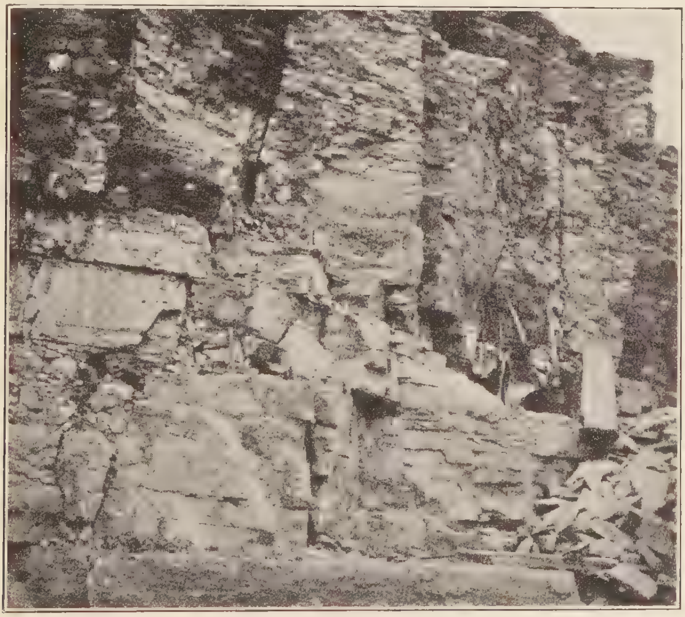


FIG. 25.—Limestone outcrop, showing joints and bedding planes along which solution can take place. Photograph by W. C. Alden. U. S. G. S. Water Supply Paper 489, plate IX, 1923.

Joints that accompany folding are classed according to their position as tensional or compressional. Their strike is usually parallel to the strike of the folds. Where joints result from torsional strains, two or more series at angles with each other are common. In such, the circulation of rock-dissolving water and the amount of pore space are materially increased.

Weathering of Rocks.—While the weathering of rocks normally results in their conversion into soils and ultimately their removal, the process may be interrupted before the removal or the disintegration have been completed. In that case the highly porous honeycombed residual debris and weathered rock may be resubmerged and covered by later sediments. Its history may be expected to follow the course taken by the normal sediment, but the product may be materially different. This is especially true when the weathered rock still retains sufficient strength and irregularity of outline of fragments to prevent compacting. If the material laid down above it is of impervious nature and not distinctly soluble, its entrance into the pore spaces of the residual matter and subsequent filling with cementing matter may not occur. In such cases highly porous rocks may result.

Nature of Rocks.—Sands and their more or less consolidated derivatives, sandstones, are the best known of the container types of reservoir rocks. Porous limestones are the only other important containers of oil. Clays and shales are the usual retainer rocks. Nonporous limestones and sandstones are also of importance. Slate-shales that are highly jointed are containers in some areas. The lesser sedimentary rocks such as gypsum, rock salt, and anhydrite, while present in oil fields, do not play an important part in concentration. In a few instances rocks that are wholly unrelated to the sedimentary types are containers or retainers. These may be either igneous or metamorphic in character.

Sands and Sandstones.—We have less definite information about the character and porosity of sands than is desirable. This is especially true of oil-containing sandstones. The difficulty in procuring actual samples of the sand, instead of merely cuttings or drillings, is great. Except where the reservoir is one containing gas under sufficient pressure to throw fragments of the stone out of the hole, the only way of obtaining an actual sample is by taking a core of the horizon. This means a considerable loss of time. Yet the value of actual samples is now widely appreciated; and the practice of taking them, a growing one.

Determination of Porosity.—After the sample has been obtained, the porosity may be determined in several different ways. According to O. E. Meinzer[1] the methods in use may be considered as falling into the following classes:

1. Measuring of the quantity of water required to saturate a known volume of dry material.

---

[1] U. S. G. S. Water Supply Paper 489, p. 11.

2. Comparing the volume of a sample with the aggregate volume of its constituents.
3. Comparing the specific gravity of a sample with the weighted average of the known specific gravity of its constituent materials.
4. Comparing the specific gravity of a dry sample with that of a saturated sample of the same material.
5. Obtaining the uniformity coefficient [1] and estimating the porosity on the basis of the observed relation between porosity and the uniformity constant.
6. Producing a partial vacuum in a vessel that contains a dry sample and observing the change in the air pressure when this vessel is connected with the air under atmospheric pressure, the volume of each vessel and of the sample being known.

Estimation of the porosity after determination of the uniformity constant by a physical analysis of the incoherent material, is the only method which can be applied to incoherent samples brought up by the bailer. Its product is strictly an empirical rough estimate, which is based upon relations observed between coherent samples and their incoherent grains after crushing the samples. The uniformity constant is determined by a physical analysis of the grains to determine the size of the grains.

The last method listed is one of recent development, but the simplicity of the principles involved makes it extremely attractive. Unless the samples are of considerable size, the measurement of small changes in gas pressures may be troublesome. The methods that require saturation of the pore space with water, namely methods 1 and 4, present considerable difficulty because of the irregularity in the rate of absorption of water by different porous rocks. In order to get any degree of completeness of saturation, the liquid must be forced in under pressures of from 50 to 150 atmospheres. Except that coherent samples must be coated with paraffin before being submerged in water to obtain the volume of the displaced water, no difficulty is encountered in finding the volumes of aggregates or of their constituent grains. Determination of the specific gravities of samples, or of the average of their component parts, depends upon measurements of their weights in air and in water. Readings are made in much the same way as volumes are taken. The United

---

[1] The uniformity constant is the ratio of the diameter of a grain that has 60% (by weight) of the sample finer than itself to the diameter of a grain that has 10% finer than itself.

States Geological Survey methods as developed and used by A. F. Melcher[1] are based upon the comparisons of volumes of the sample and the aggregate volume of the sand particles of which it is composed. The porosity is calculated from the following formula:

$$P = \frac{100(V - v)}{V}, \text{ in which}$$

P = Porosity by volume.

V = Volume of the sample.

v = Aggregate volume of the solid particles that compose the sample.

Nature of Sands.—Unconsolidated sands are generally considered as having an average porosity of from 30 to 35%. Higher percentages are common in surface sands. In loosely cemented oil sands, such as those of California, the porosity ranges as high as 40%. Many of the samples from producing horizons in that state show 30% or more. According to J. O. Lewis[2] a conservative estimate of the average porosity would be not less than 25%. Probably the porosity of Tertiary sand horizons throughout the world will not be materially different from those in California. The figure for California is cited by several authors as being applicable to Russia.

The somewhat more consolidated sands of the Upper Cretaceous show an average slightly lower than that of the Tertiary. An average of 8 samples from the Nacatoch gas sand of the Mexia-Groesbeck pool in central Texas was 24.4%. Similarly the testing of 21 samples from gas sands and associated rocks in the Shreveport gas field of Louisiana showed an average of 22.7%. A test on the porosity of a sample taken from the Second Wall Creek sand, the main oil producing horizon at Salt Creek, Wyoming, showed a porosity of 25.8.

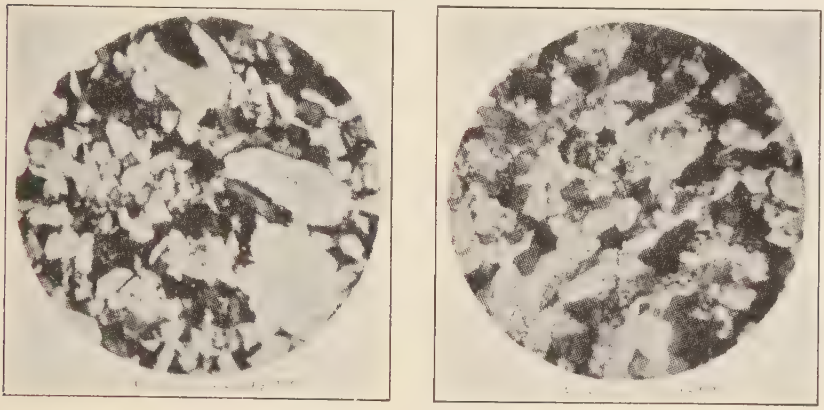
While the porosities of some samples of Paleozoic sandstones approach those of later horizons, the degree of compacting and cementation is usually so much greater than that of the later sands that porosities above 20% are unusual. It is generally considered that the production comes almost entirely from the sections in which the porosity is more than 10%. While samples of lower porosity contain oil, they are not considered representative of the true oil-bearing sand but of breaks or tight places in it or of cap or bottom strata. The average porosity of strata of Pennsylvanian age is probably higher than that of the older Paleozoic horizons.

---

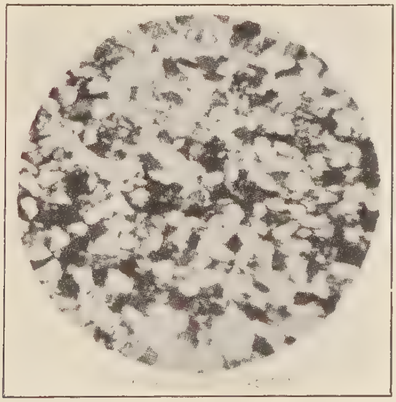
[1] Determination of Pore Space in Oil and Gas Sands, A. I. M. E. Trans., Vol. LXV, p. 474, 1921.

[2] U. S. B. of M. Bull., No. 148, p. 17, 1917.

The porosity of sandstones is determined by the degree of their compacting and the amount of cement that has been introduced.



A.—7.47 ft. below top of sand. B.—14.46 ft. below top of sand.



C.—19.35 ft. below top of sand.

Fig. 26.—Group of Photomicrographs of a Cored Portion of the Second Sand of the Venango Group, near Oil City, Pennsylvania. Taken with crossed nicols. After Fettke, Charles R.: Petroleum Development and Technology in 1926, p. 223.

It is logical to anticipate lower porosities in older rocks. However, it must be remembered that compacting is caused both by static and dynamic pressures; and that while a number of samples may be of the same age, they may not have been subjected to the same degree of compression. Similarly great differences in the amount of cement introduced are possible.

There is wide-spread feeling among drillers and field production men that the yield of oil from a sand is proportional to the size of grains which make up the container rock. This is undoubtedly true when all other factors are equal. But sands of fine grain frequently are prolific producers because of the absence of splintery and closely compacting matter. R. W. Pack[1] reports that the small grained sands are important producers in the Midway-Sunset district. He states that in many samples the percentage passing through a 200 mesh screen is equal to from 50 to 80% of the total sample. Such matter is but little larger than dust particles. Unconsolidated sands of extremely fine texture are numerous in Tertiary horizons. In California, at La Rosa in Venezuela, Baku in Russia, Trinidad and other areas, they have been the cause of both profit and anxiety. They have meant profit because of the highly saturated condition of the sands, and anxiety because of the rapidity with which such sands disintegrate and cause the hole to cave in and "sand up."

Where fine sands are continuous with coarse grained ones, the flow of oil is naturally greatest along the lines of least capillary resistance and therefore toward the wells tapping the coarse grained sands. With the introduction of cement the fine grained sand may lose its value as an oil container. Its pores, while only slightly smaller than those of the unconsolidated fine sand, become too small to permit easy flow. They may even be reduced to the size of subcapillary openings in which flow is entirely stopped. Uneven cementing may prevent circulation even though it does not decrease to any extent the porosity of the rock as a whole.

Sandstones as Retainers.—When cementation and compacting are carried to the degree where circulation is no longer possible, sandstones cease to have possibilities as containers and begin to function as retainers. Poorly assorted, fine grained sands composed of flat or other closely fitting fragments reach this stage earlier than do those of large, rounded and even grain. Beds in which the cement was partly introduced during the period of deposition are likely to reach this stage earlier than those in which the cement is all of later introduction. Sandstones composed solely of normal constituents, such as quartz and other insoluble fragmental material of grain size larger than 0.05 of a millimeter, as distinct from clays, shales, or clayey and shaly sandstones, are effective in retaining oil, gas, and water in more porous rocks as soon as their interstices become so small that gravity is unable to overcome capillary action. In other words, the retainer sandstone is one in which the pore spaces are so small that they are permanently water filled. Sandstones in which all of the pore spaces have been filled with cement would be ideal retainers, but their existence in oil fields is questionable.

---

[1] U. S. G. S. Prof. Paper 116, p. 81, 1920.

Conglomerates.—The coarse grained pebbly conglomerate is so closely related to the true sandstones that anything that has been said about the latter may be applied equally to the former. Conglomeratic sandstones and true conglomerates in which but little cement or interstitial filling has been introduced during or after deposition, form extremely fine containers of oil. Gravitational forces are fully capable of bringing about concentration of oil in such rocks, and the removal of the oil through wells is usually rapid. Conglomerates are seldom composed solely of bouldery material or even of gravel, but contain finer material, which acts as a filling. This and cementing material substantially decrease the effective pore space, sometimes decreasing it below the point where the rock can serve as a container.

Limestones.—While sands and sandstones are productive of oil in practically all of the important fields of the world, limestones are unknown as producers in many and are important in only a few. Their characteristics are much less regular than those of sandstones and have been studied less. The soft incoherent variety called chalk contains a large number of minute openings but is rarely a container of oil. In some places it is a source of water supply, but the water is taken largely from joints and solution passages. The minute size of the shells and fragments of which chalk is composed is probably the explanation of the extreme fineness of the openings and the failure of chalks to serve as containers. Practically all chalks appear to be saturated with water, but the water is apparently imprisoned in openings of subcapillary nature from which its removal is not normally possible.

The porosity of shell limestones is frequently high. Decomposition of the fleshy parts of the organisms, whose shells alone remain, gives rise to numerous and fairly large openings. In many cases the solution and redeposition of the calcium carbonate causes the filling of these openings before the rock is of great age. In others the openings, while numerous, are not connected; and the high porosity is not effective porosity. In a few, the shell porosity is maintained and may be considered as the explanation of their present effective porosity.

The prevalence of joints in limestones has been mentioned. While jointing alone may be responsible for oil accumulation in some cases, it does not appear that jointing could have been responsible for all of the oil that has been recovered from the highly jointed Trenton limestone of Ohio and Indiana. In that area two theories were advanced to explain the porosity. Edward Orton[1] maintained that the porosity was the result of shrinkage in the process of dolomitization. The joint openings were considered as of two types: those of major extent resulting from crustal movements; and those of minor extent, but far more numerous, resulting from dolomitization. A. J. Phinney[2] considered the porosity to be due to the solvent action of water percolating through rock and dissolving it along lines of weakness such as joint planes. It is entirely possible that dolomitization prepared the way for the development of a more extensive net work of joints than would be available through crustal movement alone.

The two most famous limestone producing horizons of the world are undoubtedly the Tamasopo limestone of Mexico and the Fars limestone of Persia. The production of the Fars comes from a vesicular shelly limestone. The Tamasopo is not only vesicular but in places almost cavernous. In deep strata such solution openings can only be accounted for by ground water action or weathering, when the beds were at, or close to the surface during a period of uplift at some time after they were originally deposited. The productive portions in both cases are found largely in the upper parts of thick massive and usually non-porous limestones.

Limestones as Retainers.—In contrast to the rather limited number of places in which limestones serve as containers of oil are the large number in which they are not productive. The expression "break in the lime" is common in the Eastern and Mid-Continent provinces where limestones act as retainer rocks. In such areas the break may prove to be a true porous limestone, but more frequently it is a sandy limestone and in some cases a true sandstone. The absence of oil and gas in most limestones is natural, as the calcium carbonate of which they are composed tends to pass into solution and return to the solid state easily, thus sealing any openings that are present in the lime deposits when they are first laid down. The minuteness of the pores in the incoherent chalk serves to prevent movement in that type of lime rock and permit it to function as a retainer.

---

[1] U. S. G. S. 8th Ann. Report, part 2, pp. 475–662, 1889.

[2] U. S. G. S. 11th Ann. Report, part 1, p. 617, 1891.

Clays and Shales.—Clays and shales serve as containers of oil and gas only in unusual cases. The function of these rocks is primarily that of retaining oil. The original substance of the group, clay, has as high a porosity as the average unconsolidated sand. This has been placed as high as 50%. However, the pores are, like those of chalk, so extremely small that water or other liquids entering them are able to escape from them only when the pore space is reduced by dynamic or static pressure and the liquids are forced out by decreasing the porosity. In shales the porosity is low because of the high degree of compacting of the flat kaolin particles attained with moderate pressures. The remaining pores are largely of subcapillary size and therefore unfavorable to the movement of liquids of any sort.

While not always in direct contact with the oil-containing beds, it can hardly be doubted that clays and shales have had an important part in determining the movement of oil, gas, and water in practically all of the world's oil fields.

The plastic nature of clays largely prevents the development of joint openings in them. The enlargement of such fractures is not possible as in the case of limestones because of the insolubility of the kaolin of which they are composed. Even in shales joints are uncommon. Their development is generally limited to beds which, because of their chemical or physical character, develop slaty characteristics early in their history. Jointed shales, however, are not unknown as oil producers. In some cases shale joints or crevices lie immediately above and are undoubtedly connected with underlying sandstone and limestone reservoirs. In such cases the shale fissures serve more as connecting channels and drainage pipes than as storage areas. This is undoubtedly true in the Tampico-Tuxpam field where the San Felipe shales, which lie above the Tamasopa limestone, are sometimes large and long continued producers of oil. The irregular distribution and erratic character of these wells leads to the conclusion that they do not tap a definite and continuous body of oil in the shale itself.

At Salt Creek and Teapot Dome, sensational but usually short lived flows are frequently found in the shale beds which overlie the productive horizons. Wells that strike major joints or fissures must be treated as individual finds as the individual fractures are seldom of sufficient extent to be productive in more than one well. All of the productive fractures lie above the First Wall Creek sand. Despite the fact that the sand is saturated with water below some of these wells, they do not show water. Non-oil containing crevices are sometimes entirely dry. From this it may be deduced that the crevices in this pool at least are not now connected with the lower oil containing rocks.

At Florence in Colorado fissured shales have been productive on a small scale for a number of years. The fissures follow regular systems, making possible a little geologic work in advance of the drill. The shale is the only producing horizon. The shallower wells contain gas with the oil and the deeper ones yield some water. The zone extends through a depth of 2,500 feet in the Pierre shales. While shale fissures have been found productive at other points in the Rockies, notably at Rangely and Iles in Colorado, and Big Muddy and Pilot Butte in Wyoming, the shale production has come from points overlying porous sandstones. While these may not be connected with the porous rocks below at the present time, it cannot be said that they were not in the past.

Hybrid Rocks.—Shales in many fields produce gas in limited quantities. While some of this may come from fissures, the greater part probably comes from sandy lenses and shaly sands in otherwise impervious shales. This seems to be the case along the southern shore of Lake Erie where Devonian shales appear to be the source of gas in Ohio, Pennsylvania, and New York. Similarly sandy limestones and lime sands appear as productive beds in massive limestones. Shaly limestones and lime shales or their unconsolidated representatives, the marls, function as retainers for the most part. In this they show the same characteristics that are found in the two rocks between which they lie.

Minor Sedimentary Rocks.—Coals, while frequently crossed by numerous joints and found in formations in which oil is also present, do not contain it. Neither do they serve as retainers. The explanation of this lies more in the absence of oil from the immediate stratigraphic position of the coal than in any of the physical properties of the coal itself. The conditions under which coal deposits are formed are usually responsible for the existence of shales or slaty beds both above and below them, which prevent the oil from reaching the coal. Salt, gypsum, and anhydrite, while closely associated with oil containing strata in some fields and playing an important part in the development of the salt dome type of structure, are neither containers or retainers of importance. Unquestionably they are best suited to act as retainers. While their solubility tends to the development of solution cavities, they are so incompetent and plastic in nature that these cavities cannot be maintained at any distance below the surface. In salt domes the gypsum lies directly under a limestone cap, which has been productive in some areas. It may be said to have prevented downward migration of the oil. The salt cores of these domes are commonly separated from the oil by bituminous clays or shales which prevent the oil and the salt from coming in contact with each other.

Metamorphic and Igneous Rocks.—Rocks of metamorphic nature are of too low porosity to form satisfactory oil containers except where they have developed joint planes and fissures. The same may be said of granites and other wholly crystalline rocks. Numerous instances of the existence of oil in fractures in schists, gneisses, and granites might be given, but they are without exception not of commercial importance. In addition, the oil in such rocks is found in the rotted fissured portions, which have been subjected to surface erosion at sometime or other. If commercial yields are obtained from their vicinity, they come from the porous sedimentary rocks in contact with the crystalline rocks or from zones of unconsolidated debris of conglomeratic nature which mark the unconformity between the crystalline base and the sediments. Thus, in the Panhandle area of Texas a thick basal conglomerate produced by the weathering of the underlying granite is the source of much of the oil obtained.

Basaltic sills and other forms of igneous bodies that have solidified close to the surface are only partly crystallized. They are frequently highly jointed and therefore amenable to decomposition by percolating waters. While not of commercial importance except at Furbero, jointed and altered basic igneous rocks are frequently containers of oil in the Tuxpam-Tampico area of Mexico.

Commercial importance can be given to the tuffs and tufaceous rocks formed from the consolidation of loose volcanic material on the surface. Such material is interbedded with shales and ordinary sandstones in Japan. It forms with the sandstones the productive horizons in several pools. In Texas material of the same general character has produced considerable oil at Lockhart and Thrall. Its identity is not entirely clear in these two pools. It may be either igneous material laid down on the surface or a greatly altered product of sill character. E. S. Larsen, Jr.,[1] in reporting upon a specimen taken from Thrall states as follows:

---

[1] Quoted by A. Deussen: U. S. G. S. Prof. Paper 126, p. 120, 1924.

"The material is no doubt of igneous origin, but the original minerals are now completely gone and the specimen is an aggregate of calcite, chlorite, and other secondary minerals. The form of the original lath shaped or tabular crystals is still well preserved with a texture similar to that common to basalts. The rock is clastic and probably a tuff though it may have been a flow breccia. More accurate determination is not possible, although it was without question derived from a rock closely related to basalt."

The rock is of green color both at Thrall and at Lockhart. Hence it has generally become known as serpentine. It cannot be said to be similar to the true serpentine marble or even to the serpentine formed by the hydrothermal alteration of deeply buried peridotite and other massive basic igneous rocks.

Tuffs are the product of the consolidation of volcanic ashes and dust. While sometimes dense and hard, they are more commonly porous and light. Where the ashes have fallen below the water level or were covered by water shortly after they were deposited, such ashes are frequently only distinguishable from ordinary sediments by their chemical and physical properties. Volcanic breccias are composed of the coarser fragments. Lava may also be highly porous because of the large amounts of gas and liquids that it frequently contains. Flow breccias are composed of fragments formed partly from solidified lava material taken up by that which still remained liquid and carried farther before final deposition.

Containers versus Retainers. Except with regard to sandstones and sands, very little can be said definitely about the line which separates rocks into container and retainer types. Clays because of their plasticity can only be considered as retainers. Shales unless strongly fissured must be classed with them. Chalks and limestones are normally too impervious to act as containers. Yet shell limestones, and those which have been subjected to the leaching action of water may be of high porosity and serve as excellent containers. In shales and limestones owing their porosity to jointing and to water-channeling, the porosity of the individual sample may bear no relation to the pore space of the rock as a whole. In such rocks the total porosity may be small but the recovery large because of the great ease of movement through the existing openings. Thus in limestones the sample showing a porosity of less than 10% may come from a highly productive horizon. The sandstone which showed less than that percent would be of little value.

Sandstones are not of the same character throughout the productive horizon. Lateral variations in porosity are common and are the cause underlying the development of many productive areas. Well known thick sand bodies, which were formerly considered to be of much the same character throughout their whole thickness, have been found to vary considerably in character vertically. Not only do they merge gradually into overlying and underlying shales but also prove to contain breaks or partings in which the sand is of such low porosity that it is of no value as a producer of oil. In fact such bodies of sand, though they contain no true shaly material, may serve as effectively as a shale in dividing the horizon into two parts. Analyses of the sands from different parts of the same horizon show very definitely the reasons for differences in the rate of production between

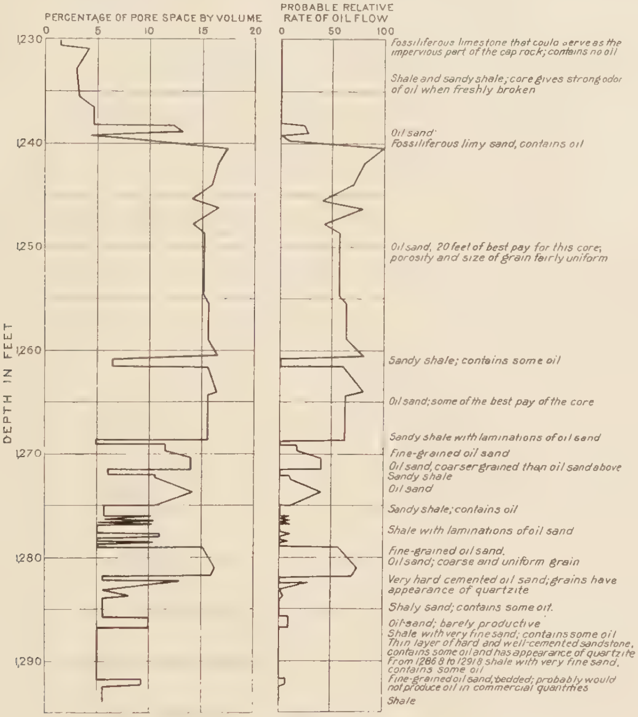


Fig. 27.—Profiles showing porosity and probable rate of flow in a core of the Bradford oil sand from a well about half a mile west of Custer City, Pennsylvania. After Melcher, A. F.: U. S. Dept. of Interior, Press Memorandum, April 17, 1925.

wells. The effects of such variations at Burbank in Oklahoma are discussed in Chapter XIV. The results of a study made by the United States Geological Survey of the variations in character of the famous Bradford sand in a cored well near Custer City, Pennsylvania, are given in Fig. 27.

From this study of the Bradford sand, it would appear that the lower limit for production is about 10% pore space; and that out of the 62 feet of thickness in the horizon, only about 37 feet can be considered as yielding oil in commercial quantities. Yet all of the sand shows oil in some quantity.

CHAPTER VIII.

THE CONCENTRATION OF OIL AND GAS.

Oilfield Waters.—Although in some pools water is not apparent in the horizons which are productive of oil and gas, it is so commonly associated with them in most areas and has such an important position in all theories of the concentration of oil and gas that it would seem advisable to devote some space to a discussion of its character and origin.

As the bulk of the sediments found in oil fields are of marine, strand line, or interior marsh or residual basin type, it is natural to assume that a considerable portion of the water that they now contain was imprisoned at the time of their deposition. Such waters are known as connate types. They may be considered as of two groups: first, the waters imprisoned between the comparatively large openings of sand, pebble, and bouldery deposits; and second, waters retained in the extremely fine and, probably in the main, subcapillary pores of clays. The first enjoy considerably greater freedom of movement than do the second. In fact, until forced out of the containing medium by decrease of pore space, clay-contained waters cannot be said to have any freedom of movement. We may go farther and say that, during the contraction period, the movement of such water is limited to movement in the shortest possible path connecting the original lodging point of the water particle and the nearest porous medium.

The similarity between the analyses of some oilfield waters and ocean waters or brines formed from their concentration leads to the conclusion that, despite the long period which has elapsed since the deposition of the containing sediments, such waters have not moved great distances from the points of their original deposition. The analyses of waters of the ocean and of the oilfield brine types cannot be said to be identical. The brines show wide variation in the amounts of the solids they contain and also in the exact ratios of the different materials present.

The most evident differences between the waters in oil and gas horizons and sea waters are the relatively high percentages of calcium and the lower totals for magnesium and for the sulphate radicle shown by the former. The absence of sulphate in deep brines is not general

TABLE 42.—COMPARISON OF ANALYSES OF WATER FROM WELLS IN THE APPALACHIAN AND ADJACENT AREAS AND OCEAN WATERS.*

Source	Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	(Br, I)	Total
Ocean water, mean of 77 analyses, salinity 33.01 to 37.37 grams per kilo	1.20%	3.71%	30.54%	1.11%	.05%	.31%	7.68%	55.21%	.19%	100%
Mediterranean Sea water, density 1.21, salinity 275.46 grams per kilo, a bittern	.26	3.72	32.06	.78	—	—	7.68	56.18	1.22	100
Artesian water, well near Pittsburgh, salinity 747.3 milligrams per liter	15.21	2.77	8.86		—	48.91	15.28	8.97	—	100
Hundred foot sand water, oil well in Center Township, Butler Co., Pa., salinity 122.16 grams per kilo	8.57	1.46	27.34	.20	none	none	.02	61.97	.16	100
Big Lime Sand, oil well in Melaga Township, Monroe Co., Ohio, salinity 141.13 grams per liter	8.19	1.30	27.82	.49	none	.3	none	62.00	—	100
Berea Sand, gas well, Marion Township, Noble Co., Ohio, salinity 53.06 grams per liter	5.18	1.63	29.88	.96	none	.70	none	60.44	—	100
Well near Cincinnati, Ohio, salinity 10,589 parts per million, artesian well	3.72	1.13	33.09	.27	2.63	—	3.12	55.83	.07	100
Blue Upper Lick Spring, Kentucky, salinity 11,068 parts per million	3.56	1.57	31.47	.96	2.34	—	6.03	53.08	.53	100

* Analyses after Mills, R. Van A., and Wells, Roger C.: U. S. G. S. Bull. 693; and Clarke, F. W.: U. S. G. S. Bull. 770.

except where those brines have come in contact with organic matter which has combined with the sulphate. In the analyses of waters from wells not connected with oil-producing horizons given in Table 42, the sulphate content is not as low as it is in the samples from the oil horizons. The low content of magnesium and the high percentage of calcium are in keeping with the widely held belief that dolomitization of limestones is a secondary process in which the calcium of the original limestone is replaced by magnesium from waters coming in contact with it.

Such similarity in content as is shown between most of the waters of the Appalachian area and those of the ocean can only be accounted for by the assumption that the horizons in this area were not open to infiltration of surface waters after the period in which they were deposited. The high degree of concentration may be due to concentration at the time of their imprisonment but may also be considered as resulting from concentration after deposition. The exact manner of this later concentration is unknown, but its accomplishment can hardly be doubted. In a few instances it may be traceable to the solution of beds of rock salt or salt-containing rocks, but this explanation is not applicable in the majority of cases. Possibly evaporation under the influence of a temperature somewhat greater than that at the surface has been a contributing factor. Moving gases may have been instrumental in causing vaporization and escape in other cases.

The waters contained in the oil-bearing horizons of the Salt Creek pool of Wyoming are as closely related to surface waters of today as those of the Appalachian are related to ocean waters. The analyses listed in the Table on page 184 are all from surface or oil horizons in this pool.

The Shannon sand outcrops in part of the pool. It contains some oil but has never been an important producer. The top of the First Wall Creek lies at a depth of 900 feet below the surface in the center of the structure and at much greater depths on its edges. The shale fissures that yield oil from points above it are found at different depths in different wells. They are not continuous. About 400 feet below the First Wall Creek sand lies the Second Wall Creek. The Third Wall Creek, a comparatively unimportant horizon, lies underneath this. Below this sand lie the Dakota sand, the Lakota sand, and the Sundance formation in the order given. The Dakota is lenticular and contains only a small amount of oil in this pool. The

Lakota is believed to contain oil in amounts comparable with the First and Second Wall Creek sands, but neither it nor the Sundance have been fully tested.

The analyses given are only representative of the water in the different horizons. There is a difference in the total salinity of waters from different wells penetrating the same horizon. In the First Wall Creek the salinity ranges from 3,000 to 14,000 parts per million in 22 samples listed by Young and Estabrook. Similarly the salinity in the 6 samples of the Second Wall Creek shows a range of from 12,108 to 20,141 parts. The outstanding characteristic of all the waters from the Shannon down to the Sundance is the high proportion of bicarbonate. With the exception of the Shannon and Dakota, which are not important oil horizons, sulphates are lacking in all the waters. In the former, the connection with the sulphate water of the surface is very close. In the Dakota, the sulphates have not been altered because of the limited amount of organic matter. The shale water shows an abnormally high chloride content for its stratigraphic position. This may be cited as further indication of absence of direct connection between the fissures and the lower oil-producing horizons, which has been referred to previously. In none of the horizons do chlorides dominate the waters as they do in the waters of the eastern fields. Moreover, the chloride content does not vary with depth as

Table 43.—Analyses of Waters at Salt Creek, Wyoming.*

In Part Per Million.

Source	Na	Ca	Mg	SO_4	Cl	CO_3	HCO_3	Total Solids
Surface	577	148	103	1811	20	—	152	2811
Shannon Sand	1057	30	80	1730	52	66	880	3895
Shale Well	2738	8	—	—	2920	—	2260	7926
First Wall Creek Sand	2808	Trace	15	—	865	113	5810	9611
Second Wall Creek Sand	4602	12	9	Trace	5125	—	3480	13288
Dakota Sand	4519	78	47	267	6208	—	1434	12553
Upper Bench of Lakota Sand	1302	25	18	—	332	—	3050	4727
Lower Bench of Lakota Sand	1281	7	—	—	586	—	2390	4264
Sundance Sand	2308	15	8	—	2272	—	2290	6893

* Typical analyses selected from a group given by Young, H. W., and Estabrook, E. L.: Petroleum Development and Technology in 1925, p. 256.

might be expected. The Lakota is especially deficient in chlorides, while the Dakota, which lies immediately above it, shows the highest content of any of the horizons tested.

The analyses of the several waters show very clearly that surface waters have entered the oil horizons on a large scale. It is probable that they are still entering them today. Differences in character in different parts of the same horizon may be accounted for by differences in porosity, which cause differences in the ease of circulation and in the reactions between the waters and the rocks through which they flow.

The sand horizons of the Cretaceous Powder River Basin, upon whose western edge the Salt Creek structure lies, are evidently continuous over wide areas. This is certainly true of the major producing sands. Unlike the earlier Eastern Paleozoic Basin, which has never been elevated much above sea level, practically the whole of the Cretaceous in this area lies above the level of the sea. Escape of the original waters has probably been encouraged. The entrance and substitution of waters of later age and of entirely different character, because of continental origin, has been greatly assisted.

In the Valley Field of California, the sand horizons that contain oil are much thicker than the horizons of the Rockies or of the eastern Paleozoic areas. The individual sand beds are less continuous and subject to rapid variations in porosity. Thus some of the waters associated with the oil-producing zones of California resemble closely the waters of the surface, others show a definite connate character, still others are apparently combinations of the two. Shallow waters from water wells and top waters in oil wells show a wide range in composition but commonly have a high sulphate content in comparison with the chloride and even the carbonate totals. The modified meteoric waters show substantial increases in carbonates, accompanied by a corresponding decrease in sulphates. The decrease in the sulphate is further accentuated in the meteoric waters that have been in contact with the oil for a longer period of time. Analyses of the unaltered brines are not available in the vicinity of the oil wells, but would probably differ mainly from the altered ones given in the percentage of sulphate matter contained. The differences between the chloride and carbonate contents of the waters that are considered as primarily of meteoric origin and those that are called connate are very marked.

Oilfield waters are commonly under considerable pressure. In

TABLE 44.—ANALYSES OF WATERS IN SAN JOAQUIN VALLEY, CALIFORNIA.*

In Parts Per Million.

Source	Sodium & Potassium	Calcium	Magnesium	Iron Oxide and Alumina	Sulphate	Nitrate	Chloride	Carbonate	Bicarbonate	Sulphide	Silica	Total
Surface water, Fraziers Spring, sec. 2—T30S—R27E....	216	92	87	—	580	Tr.	70	0	433	—	87	1345
Shallow water, 2–19–15..............	470	59	34	Tr.	914	—	88	140		—	44	1749
Top ground water, 10–19–15............. (Also contained 14 parts dissolved H_2S)	596	163	9	102	1276	—	140	117		—	3	2406
Top ground water, 26–19–15..............	661	249	148	105	1793	—	368	169		—	—	3493
Modified ground water, 26–19–15..............	1003	17	9	4.8	231	—	54	1067		52	60	2497.8
Altered Meteoric water, 29–29–15..............	799	62	28	15	22	—	480	784		—	86	2276
Altered connate water, 28–31–23.............. (K 124 parts)	11160	848	425	—	0	—	20694	48	359	—	102	33578
Altered connate water, 28–32–24..............	9855	1064	345	5	0	—	17231	692		—	10	29202
Altered mixed waters, 15–32–23..............	3921	37	41	Tr.	1	—	3977	0	3855	—	136	10011

* Selected from groups of analyses given by Rogers, G. S.: U. S. G. S. Bull. 653, 1917.

some cases the water is under such pressure that it rises to the surface from a horizon located several thousand feet below that surface. In some cases the water may flow out in the same way as artesian waters do. As a matter of fact, the waters of pools like Salt Creek can hardly be considered as other than modified artesian waters. In such cases the head may gradually decrease until the water ceases to flow. In the majority of cases the water rises only a few hundred feet in the hole. In some it may flow in so rapidly that it is impossible to bail the hole dry, yet not be under sufficient pressure to rise to the surface. In a great many cases the amount of water contained in thin and probably lenticular sands is not large, and they are soon exhausted by bailing.

Some sands are saturated with water, but capillarity prevents its movement and entrance into the holes. Such sands are considered by drillers to be dry. Sands that contain larger pore spaces but are only partly saturated with water are not uncommon. These are most prominent in the upper portions of wells in strata lying above sea level. Deep sand horizons lying below sea level which are devoid of water are not unusual. While many are not capable of absorbing water because of the small size of their interstitial openings, others appear to be capable of absorbing unlimited quantities. The explanation of the occurrence of such bodies in the deep horizons of the Eastern and the Mid-Continent Paleozoic Geosynclines is difficult. Such sands are usually lenticular beds rather than thick or extensive ones. Possibly the beds have only been partly filled since the time of their deposition. They may have lost the bulk of their original water content during periods of compacting; and now, with the release of pressure through removal of part of the overburden by weathering, they have less than enough to fill the pores of a slightly expanded rock. The water may have been given up through evaporation.

The explanation of drainage during periods of uplift may be offered but can hardly be given much value in areas where there is no evidence that such drainage was possible. In addition, the unsaturated beds of the Appalachian area are frequently found in close proximity to those which are filled with water. The latter are frequently much more continuous and therefore much more liable to drainage and loss of water in other ways than the dry beds themselves.

The Gravitational Theory.—If oil, water, and gas are placed in a closed vessel or tank, they quickly arrange themselves into layers according to their densities, water on the bottom, gas on top, and oil in between. The separation is evidently due to difference in density and nothing else. In general the same positions are taken when these substances are found in association with one another in the pore spaces of rocks. This arrangement is the basis for the gravitational theory of separation, which is the underlying principle of all well locations made by geologists at the present time. The shape of the porous rock container is naturally different from that of the tank. Its horizontal dimensions are of great extent compared with its height. Furthermore, the quantity of oil and gas present is usually very small in comparison with the amount of water present. Any large accumulation of oil implies a considerable amount of horizontal movement as well as vertical movement. The first structural condition noted as being associated with oil yielding areas was the anticline. Because of this the theory of gravitational accumulation soon became known as the anticlinal theory. It was long the subject of controversy, largely because of the failure of many to recognize that the conditions postulated by the adherents of gravitational separation were not limited to the anticline but could be produced by a number of different structural forms.

History of the Theory.—The separation of gas and oil from water and their accumulation in the upper and domed portions of beds seem to have been recognized immediately after the discovery of oil in the Ontario and Appalachian areas. Articles by E. B. Andrews[1] and J. S. Hunt[2] show appreciation of the relation of oil to structure as early as 1861. The theory was developed and clarified by other writers in the years following. Among the better known writers dealing with the subject were Alexander Winchell[3] and J. S. Newberry.[4] However, the theory cannot be said to have been generally accepted before the present century. The greater part of the exploration work done up until 1890 was in the Appalachian field. The connection between the occurrence of oil and structural conditions is not always clear in this area because of the number of other factors, such as absence of water, lenticularity, and variation in degree of cementation, which are present.

---

[1] Rock Oil, Its Relations and Distribution, Am. Jour. Sci., 2d ser., Vol. 32, pp. 85–91, 1861.

[2] Notes on the Geology of Petroleum or Rock Oil, Canadian Naturalist, Vol. 6, pp. 241–255, 1861.

[3] On the Oil Formation in Michigan and Elsewhere, Am. Jour. Sci., 2d ser., Vol. 39, p. 352, 1865.

[4] Devonian System, Ohio Geologic Survey, Vol. 1, p. 160, 1873.

The real development of the theory and the beginning of its use in a practical way may be said to have begun with the work of I. C. White[1] in 1885. Edward Orton[2] applied the theory to the development of the Lima-Indiana district and reported that the areas of greatest accumulation corresponded with those which were favored by the theory. Orton's greatest contribution to the science of petroleum geology was the drawing of a contour map showing for the first time in a clear and understandable manner the relation between oil occurrence and structural conditions.

I. C. White amplified his earlier statements in another paper[3] in 1904 which may be said to mark the close of discussions concerning the principles of gravitational or anticlinal accumulation and their general acceptance as a guide in prospecting. While accepting the principle, many geologists did not feel that gravity alone could bring about segregation in the manner postulated. In 1909 M. J. Munn suggested the modification now commonly referred to as the hydraulic theory, and in 1914 C. W. Washburne brought up the question of the importance of capillarity in the concentration of oil. In 1912 R. W. Johnson pointed out the importance of natural gas in the movement of oil. In 1910, L. Mrazec, and again in 1917, M. Daly proposed the diastrophic theory of oil migration, in which accumulation was considered as caused by deformative movements in the earth's crust. These modifications were developed to explain conditions in particular areas and are not always applicable to all areas.

Expulsion of Oil from Non-porous Rocks.—All of the theories explaining accumulation are based upon the assumption that the oil is contained in a porous medium into which it has migrated from a non-porous original source bed as outlined in Chapter IV. The generation of the oil is considered as due to compacting by static pressure and by dynamic agencies of the clays in which the oil-source materials were contained. The history of these clays seems to indicate that a period of dehydration, in which a large part of the water content was displaced, occurred early in the stage of compacting. The stage in which the organic matter was changed into free-moving liquids and gases and expelled must have been later than this. In a sense the expulsion may be considered as caused directly by the pressure that was applied to the shale or clay. However, pressure may be better considered as the indirect agency, as the pore space in highly compacted shales is not entirely destroyed. Water seems to have been a more active agency. The water remaining in the interstices of the clay or shale had the power of maintaining itself there because of its high surface tension. It was then capable of forcing oil and gas into the more porous container types of rocks. The movement of oil and gas globules through the extremely fine capillary and subcapillary openings of clays and shales cannot be considered as due to gravity. Oil containers, whose only possible source of oil is a particular black shale, lie above and below that shale source. In the migration of oil and gas to the porous beds, fractures and fault planes probably assisted materially.[1]

---

[1] The Geology of Natural Gas, Science, Vol. 6, June 26, 1885.

[2] The Trenton Limestone as a Source of Petroleum and Inflammable Gas in Ohio and Indiana, U. S. G. S., 8th Ann. Report, part 2, pp. 475–662, 1889.

[3] Petroleum and Natural Gas, West Virginia Geol. Sur., Vol. A, pp. 48–64, 1904.

Manner of Accumulation.[2]—Oil and gas escaping from the shale into a more porous sandstone or limestone enter a medium that may be either completely saturated with water, partly saturated, or entirely dry. Where partly saturated, the water will be found in the lower portion of the container while the upper will be dry or filled with water vapor.

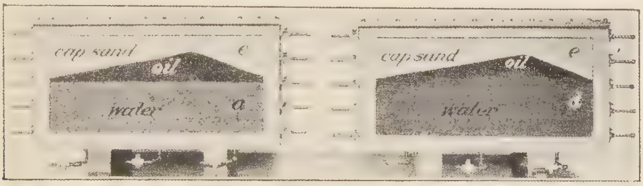
The oil entering a dry sandstone will flow downward as long as gravity is sufficient to overcome friction and capillary attraction. The gas will diffuse with the air or water vapor if any be present to fill the pores of the rock. In such cases the principal points of accumulation of oil will be near or at the bottom of synclines. Where beds are lenticular, accumulation will occur in the lowest points of the lens or the porous portion of the containing medium. If the bed is continuous over a wide area but its slope is variable, the oil may be expected to remain at points where the slope is reduced to so great an extent that friction overcomes the force of gravity.

According to the gravitational theory, if oil or gas enter a porous rock that is completely filled with water, they will, because of the differences between the densities of the hydrocarbons and the water, immediately rise to the top of the porous stratum. If the slope of the bed is sufficient to overcome friction, the oil and gas will gradually move up the slope, the gas rising to higher places than the oil. If the beds are horizontal or nearly so, there will be no horizontal movement, as the force supplied by the differences in density between the hydrocarbons and the water cannot be resolved into horizontal and vertical components. Commercial accumulation in water-filled strata will be limited to the crests of anticlines where the porous strata are continuous over wide areas and distinctly folded. Where they are lenticular or variable in porosity, the oil and gas will be found occupying the highest portions of the lenses or porous bodies. Where the beds are continuous but tilted rather than folded, accumulations of oil and gas may be expected in the comparatively flat terrace areas which interrupt the general slope.

---

[1] McCoy, A. W.: Jour. of Geol., Vol. 27, p. 261, 1919.

[2] For a concise general statement of theory see Griswold, W. T.: U. S. G. S. Bull. 318, pp. 12–21, 1907. For experimental proof of theory see Mills, R. Van A.: Econ. Geol., Vol. 15, pp. 398–421, 1920.



(1) (2)

FIG. 28.—Experiment showing the gravitational segregation and accumulation of oil in sands of different textures. Tank 1 contained a relatively coarse sand (*a*), and tank 2 a relatively fine one (*d*). The cap sand (*e*) was water-saturated. After Mills, R. Van A.: Econ. Geol., Vol. 15, p. 404, 1920.

If the hydrocarbons enter a medium that is only partly saturated with water, the action will be a combination of the two types. The gas will diffuse into the upper portion of the horizon as previously, but the oil entering it will move upward or downward in the horizon according to whether it enters above or below the top of the water surface. Ultimately it will take a position of rest upon the water surface. The oil surface while in contact with gas will be in contact with a highly diffused type of gas. If the horizon is continuous over a wide area, the gas may appear to be entirely isolated from the oil. The oil may be expected to occupy an approximately level belt surrounding a water-filled syncline. If the beds are lenticular, the belt will be limited to the extent of the porous portion at that level. The oil-water contact in different horizons within the same basin, or in portions of the same bed separated by non-porous sections, may be different.

It is apparent that friction will tend to retard the gravitational movement of gas less than it will that of oil. The concentration of gas in anticlines and in the highest parts of lenticular bodies on the flanks of basins will be more frequently in direct keeping with the relationship postulated by the gravitational theory. This is found to be the case in practically all fields.

Objections to the Theory.—M. J. Munn[1] raises the objection that the force available for movement of the oil through differences in gravity between oils and waters is not sufficient to cause the movement indicated. He also questions its adequacy as an explanation of the high pressures under which oil and gas are found. He points out that the maximum dip in the Hundred-foot sand in productive parts of the Appalachian field is not more than one foot to fifty and that the average is only one to seventy-five. The crude oil produced has a density of 0.7977 and is associated with salt water having a density of 1.0623. The difference between them is 0.2646, a figure which is equal to about 30% of the weight of the oil. However, in areas of maximum dip, the force available for movement along the dip would be only .0067 of the weight of the globule of oil. He further points out that this force is opposed by molecular repulsion of oil and water, capillary adhesion, interstitial molecular cohesion (which is proportional to the viscosity of the oil), and both static and kinetic friction.

There are a number of large pools in the Appalachian area in which the dip averages less than 30 feet to the mile. As the force available to produce horizontal movement equals only .00187 of the weight of the oil in such areas, he concludes that slight irregularities in the roof of the porous horizon would be more than sufficient to overcome the force of gravity and that concentration areas would be limited to a few acres.

Further question is brought up by the difficulty of explaining by gravity alone the action of wells. While in wells drilled into fissured limestones of the Tampico-Tuxpam area the salt water follows rapidly upon the exhaustion of the oil, this is not always true even in pools where the oil is known to be surrounded entirely by water. In a number of instances oil and gas have been found up the slope from areas in the same horizon that were devoid of liquids or gases of any sort. Yet their yield has been continuous over long periods. Similarly oil and gas have been produced under pressure from pools which are considered as being down the slope from unsaturated portions of the same horizons. Critics of the gravitational theory point out that such yields are not in keeping with that theory.

---

[1] Economic Geology, Vol. 4, p. 150, 1909.

Recent studies lead to considerable doubt as to whether the unsaturated dry portions are actually continuous with the producing areas even though they are in the same general horizon. Before it became customary to take cores, the only means of judging the poros-

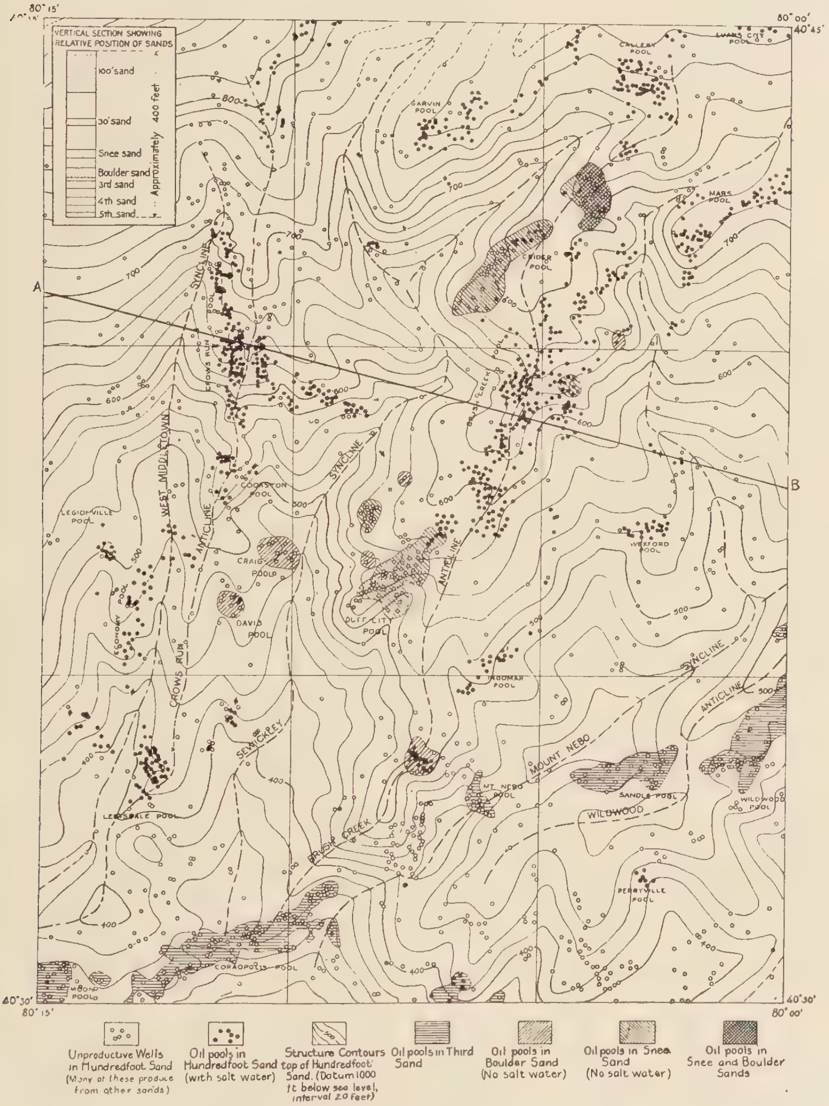


FIG. 29.—Map showing Oil Wells in Sewickley Quadrangle, Pennsylvania. After Munn, M. J.: Econ. Geol., Vol. 4, p. 143, 1909.

ity of sands was by examination of the bit cuttings removed from the well or the small fragments thrown out by gas or adhering to the bottom of the bit. As already pointed out, porosity is not directly proportional to the size of the grain. Yet until recently porosity has been judged almost entirely upon that basis by drillers and even by many geologists.

Secondly, it is questionable whether water is actually absent from so-called dry sections. Capillarity would serve to retain water in those sands in which it was not under high pressure or in which the capillary channels were of fine nature.

The steady flow of gas and the slow flow of oil filtering into the bottom of a well indicate that the hydrocarbons are under pressure in the containing medium. Such conditions could not exist in unsaturated containers, unless the unsaturated container has been subject to alteration subsequent to the accumulation of the oil and gas in it. Such alteration is to be expected, however. It is the natural accompaniment of continued compacting and the first stages of metamorphism. In areas in which old and largely compacted sediments are the producers of oil, such as the Paleozoic rocks of the Eastern and Mid-Continent Provinces, compacting may be considered as an important agency in placing hydrocarbons under pressure subsequent to their concentration by gravitational means. The gas in such deposits may in no small measure owe its existence to the same dynamic agencies.

The Hydraulic Theory.—There still remain points that are not clear and are more easily and clearly answered by the utilization of

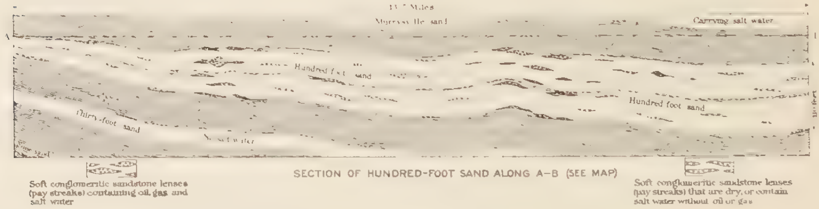

Miles
Murrysville sand
Carrying salt water
A
Hundred foot sand
Hundred foot sand
Thirty-foot sand
Salt water
SECTION OF HUNDRED-FOOT SAND ALONG A–B (SEE MAP)
Soft conglomeritic sandstone lenses (pay streaks) containing oil, gas and salt water
Soft conglomeritic sandstone lenses (pay streaks) that are dry, or contain salt water without oil or gas

FIG. 30.—Cross-section of the Hundred-foot Sand in the Sewickley Quadrangle, Pennsylvania, along line A–B. After Munn, M. J.: Econ. Geol., Vol. 4, p. 145, 1909.

forces other than the gravitational differences between oils and waters. As the hydraulic theory was the first of the substitute theories suggested and has received more publicity than the others, it should be considered first. This theory was advanced by M. J. Munn[1] to explain the irregularities in the occurrence of oil throughout the Appalachian region. He considered petroleum to be formed during the decay of organic matter rather than subsequent to the burial of the sediments. He believed that the oil was held to the clay particles by adhesion. Water circulating through the more compacted clays and shales was considered to have been the agency breaking down the adhesion of clay and oil particles. After the oil had been freed, it was forced into the porous sandstones in the form of a more or less complete emulsion of oil and water.

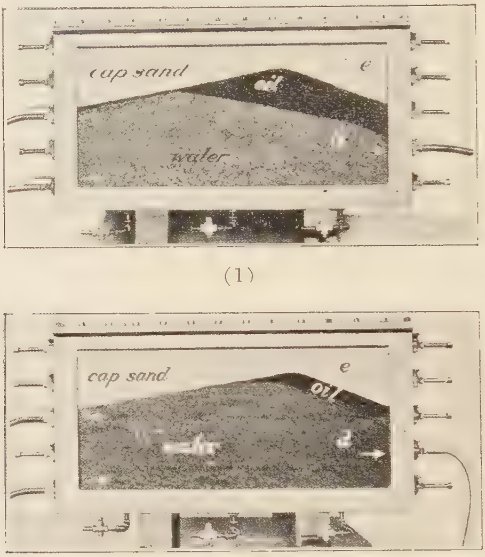
According to Munn, water moved through rocks mainly under the driving influence of the weight of a column of water behind it when the pores were large, and the squeezing, drawing, or pulling effect of capillarity when the pores were small. In either case or in cases where the two forces worked in concert, the action was opposed by friction. Movement through the different portions of the same bed would not be uniform but would be most pronounced through the larger pore spaces and slowest in the rocks having the smallest openings. Hydraulic pressure appears to have been considered as the more important force in the theory; and the slower capillary movement, only utilized to explain movement when the hydraulic element became exhausted by friction.

The water moving in this manner would push ahead of it a considerable portion of the oil and gas contained in the beds and would occupy the space originally taken by them because of its greater capillary force. Movement through different beds would not be uniform and would eventually result in zones of conflicting currents of water between which the oils and gases would be trapped and held in the more porous bodies into which they had been forced.

Thus water passing through a shale largely by capillarity would force an oil into a sandstone where capillarity would be too weak to function. Pay streaks might be expected to occur in the more porous sections. Munn concluded that some pools would be formed solely by capillarity, others by hydraulic pressure, and a third type by a combination of the two agencies. While the pressure was originally due to the hydraulic and capillary forces that brought about the accumulation, it was considered as having been maintained by the expansive force of gas that accumulated with the oil or was formed subsequently. This gas was not able to diffuse because of the saturated condition of the surrounding rocks. He suggested that if the individual pool owed its origin to hydraulic circulation, water would be expelled with the gas or oil; if solely to capillary action, the water would remain in the beds even though they were saturated with it. Rocks that contained no water were lacking in water solely because they had never been invaded by waters of the hydraulic type.

---

[1] Economic Geology, Vol. 4, pp. 509–529, 1909.



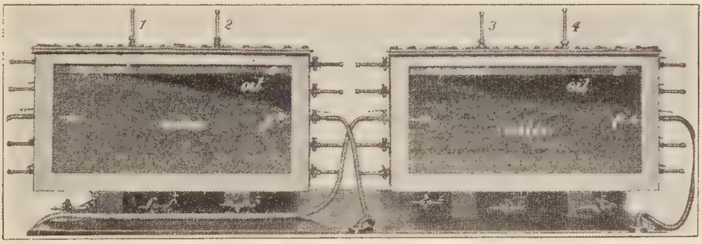
(1)

(2)

FIG. 31.—Experiment showing gravitational and hydraulic segregation and accumulation of oil in sands of different textures. Tank 1 contained a relatively coarse pay sand (*a*) and tank 2 a relatively fine one (*d*). The cap sand (*e*) was water saturated. After Mills, R. Van A.: Econ. Geol., Vol. 15, p. 404, 1920.

The first criticism of the theory as suggested by Munn is that of the use of the term "hydraulic" when the theory depends as much upon capillary phenomena as upon hydraulic action. Also the penetration of shales and clays by water with the freedom suggested is open to question. Waters in different horizons of fields where circulation of water is most pronounced show marked dissimilarity of character in closely allied horizons. The shale water in Salt Creek, an analysis of which is given on page 184, shows a difference in character from the waters both above and below it not in keeping with the theory. Similarly the lenticular sand bodies in the Monterey shales of the Valley Field of California contain connate waters bearing absolutely no relation to the waters in nearby and more extensive horizons.

The close similarity in the analyses of waters in the Appalachian field with ocean waters, as compared with the differences between the waters normal to oil horizons at Salt Creek and those of the ocean, leads to the conclusion that circulation has been very slow if it has occurred at all in the older Paleozoic horizons. While the Appalachian area was subjected to several periods of flooding before its final uplift, it does not appear that it was uplifted at any time sufficiently to permit the weathering of its deeply buried sediments and allow the removal of their original waters. Unless this be admitted, the movements postulated could not have occurred.



(1) (2)

FIG. 32.—Experiment showing differential movements between oils of different viscosities and water, under same conditions of hydraulic flow. Tank 1 contained relatively non-viscous Appalachian oil; tank 2 more viscous Mid-Continent oil. After Mills, R. Van A.: Econ. Geol., Vol. 15, p. 405, 1920.

The importance of capillary action in forcing oil from shales into sandstones has already been mentioned. Its function in promoting concentration in the porous horizons may more properly be considered in discussion of the views advanced by Washburne. The suggestion, that water moving through sandstones or other porous rocks under hydraulic pressure will advance at different rates owing to differences in porosity in parts of the beds through which it passes, is logical. That it is capable of moving along in front of itself or carrying along with it a quantity of oil has been demonstrated by the success of water flooding operations in the Bradford district in Pennsylvania. To what extent it may be considered as causing permanent accumulations of oil is open to question. The areas in which circulation of water is most clearly shown are sections in which the accumulation of oil is most definitely restricted to anticlinal and other areas favored by structure.

This conclusion of Munn[1] will be generally admitted: "The structural position of a pool may be said to depend upon the direction of movement of the invading water with reference to the dip of the rocks. If the course of the water was parallel to the dip of the rocks and the movement by hydraulic pressure, the position of the oil pool will conform closely to the structure lines."

His further conclusion, that if the water had a direction parallel to the strike, the pools may have no definite structural arrangement, is not sufficiently supported by evidence to be generally accepted. In both cases, permanent accumulation is likely to be found to coincide with areas that are structurally favorable. On the other hand, there is good reason to believe that moving water may be an important agency in hastening accumulation. It may also serve to determine the commercial importance of individual structures by altering the lines of drainage during the period of accumulation.

The view of moving water as a modifying agency rather than a sole agency of accumulation was advocated by E. W. Shaw[2] in 1917 and later by J. L. Rich[3] in 1921. The former applied it to conditions in the Appalachian field and the latter to parts of the Mid-Continent and Gulf Coast areas. The writer would consider its application even more probable in the Rocky Mountain areas where circulation is more clearly outlined, as in the Powder River Basin.

Capillarity as a Means of Concentration.—While various writers had mentioned capillarity as a modifying agency in the accumulation of oil and Munn had utilized it in connection with hydraulic pressure, the first to consider capillarity as the prime means of concentrating oil was C. W. Washburne.[4] Briefly stated, his hypothesis is that water, which has a surface tension approximately three times that of oil, will tend to maintain itself in the finer pore spaces and to displace oil and gas from such pores and force them into the larger pore spaces of rocks. It will be noted that this does not necessarily mean into sections of greater porosity. Normally, however, the beds having the large interstices are also the beds of high porosity.

The views of Washburne were supported by tests of the surface tensions and other capillary phenomena displayed by crude oils and their individual compounds. Experimental proof of the hypothesis was offered by A. W. McCoy.[1] In one experiment he placed a clay saturated with oil in contact with a sand saturated with water. The portion of the clay not filled with oil was filled with water. The oil tended to move into the sand, the water from the latter taking its place in the clay. This experiment was followed by others in which it was demonstrated that oil would move along fault planes or similar openings toward porous sands from which they were separated at all other points by water-soaked clay or mud.

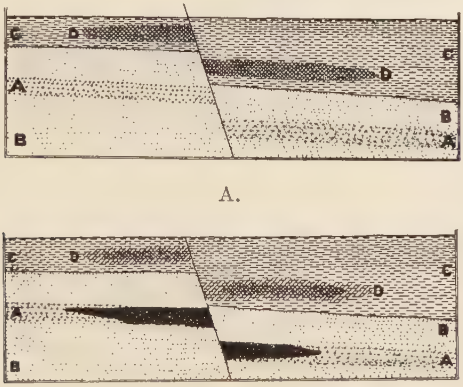
---

[1] Idem, p. 529.

[2] Economic Geology, Vol. 12, pp. 610–628, 1917.

[3] Economic Geology, Vol. 16, pp. 247–271, 1921.

[4] A. I. M. E. Trans., Vol. 50, pp. 829–842, 1914.



A.

B.

FIG. 33.—Diagrams showing accumulation of oil by capillary forces. A, Before removal of partition, showing oil in shale marked "D." B, After removal of partition showing oil partially replaced from "D" and accumulated in "A." After McCoy, A. W.: Jour. of Geol., Vol. 27, pp. 255, 256, 1919.

This experiment consisted in placing in a glass box a water-soaked sand bed B in which layers of coarser sand A were placed. Two series of these coarser beds were made and placed at different levels to simulate the conditions adjacent to a normal fault. Above the sand, the water-soaked mud C containing a layer of oil-soaked mud was laid so that it occupied a position parallel to that of the sand layers. When the beds were in place, the celluloid sheet, which represented the fault and served to keep the material apart during the placing, was removed without disturbing the strata. Within an hour after the removal of the sheet, McCoy reports that oil began to collect in the layer of sand having the largest pores and continued to move into the porous layers until all of the coarse sand was nearly filled on each side of the plane representing the fault. Water had in the meantime partly replaced the oil in the overlying oil-soaked mud.

---

[1] Jour. Geol., Vol. 27, pp. 252–262, 1919; and Vol. 24, pp. 798–805, 1916.

Capillary attractions decrease with increasing temperature and may therefore be expected to decrease with depth. Washburne considers that capillary action would lose half of its strength at a depth of 5,000 meters if the average increase of 1° C. for every 30 meters of depth is maintained. If increase in temperature were more rapid as seems to be the case in some areas, the decrease in capillary force would occur sooner. As the surface tensions of oils decrease less rapidly with increasing temperature than do those of water, it is evident that capillarity will not be as effective a force at 3,000 or 4,000 meters below the surface as it is at the surface. However, such depths are considerably greater than those reached in any of the wells drilled up to the present and may not have been reached by the sediments in the Appalachian geosyncline at any time during their history.

Gas cannot be drawn into capillary openings by surface tension. While globules of gas imprisoned in minute pore spaces resist the entrance of water and their own displacement, they can readily be forced out of these pores into larger ones. The resistance to movement of diffused bubbles of gas or of bubbles of oil by water may be traced to the immiscibility of these substances with water. The oil and gas entering a water-saturated rock round off into bubbles, which are less able to move through the restricted openings connecting the larger pore spaces. It is questionable whether capillarity can then be considered as an agency of movement of oils through nearly horizontal water-saturated rocks having the same size of openings. However, where there are variations in the size of the pores, capillarity will force the oil and gas into the larger openings regardless of their position from the starting point. Pay streaks in sand bodies or in limestones, in which the oil and gas are definitely limited to thin coarse portions of horizons of much greater thickness, may be traced to capillarity. Because of the resistance offered by immiscibility and relative viscosity, capillarity is much more able to function in beds that were originally dry or only partly saturated.

The Function of Gas.—The difference in the resistance to separation by either gravitational or capillary means given by natural gas and offered by oil is widely known. Because of the ease with which gas appeared to be concentrated, R. H. Johnson[1] suggested that moving gas was responsible for the ease with which oil had apparently moved through the pores of rocks. He considered the oil to be carried as a film on the gas bubble.

---

[1] Science, New Series, Vol. 5, pp. 458–459, 1912.

Gas is soluble in oil. The amount of gas held in solution is approximately proportional to the pressure exerted upon the gas. The buoyancy and decrease in resistance to movement of oils in strata under high pressure lend material aid to movement. In strata that are not under pressure, the disseminated occurrence of gas and oil particles opposes such motion through the action of immiscibility. The rôle of gas under pressure in promoting movement is widely recognized today in the application of back pressures to oil wells to prevent the loss of oil and in the introduction of air and gas into wells. The ability of gas to move oil, while dependent upon the amount of gas dissolved by the oil, may be considered as being also a function of the pressure. The movement of oil under the influence of dissolved gas is maintained only in largely saturated media in which there is no separation of dissolved gases through decrease in pressure. The importance of this factor was early recognized in processes of introducing artificial air and gas pressures into wells to promote the movement of oil to centrally located pumping wells.

Effects of Temperature.—Washburne pointed out the decrease in the strength of capillarity with increased temperatures when he proposed this force as a major one in the concentration of oil and gas. Increased temperature will bring with it reductions in viscosity that may have an important bearing upon the movement of oils at relatively moderate depths. Both the reduction in viscosity and capillary strength must be considered as favorable to accumulation following the lines laid down in the gravitational and the hydraulic theories, as such changes permit the full strength of gravity to be utilized.

Effects of Diastrophic Movement.—Compacting of sediments through increasing static pressure plays an important rôle in causing the reduction of pore space in sediments and thus is directly or indirectly responsible for the initiation of the movements suggested. Dynamic pressure materially assists in compacting. According to L. Mrazec[1] and Marcel Daly,[2] the forces resulting from diastrophic movements in the earth's crust are the most potent causes of the migration of oil and gas. The movement of liquids and gases is considered to have been initiated by differences in pressure within the crust caused by differences in the intensity of the diastrophic action in different areas, or irregularities in the manner in which different rocks react to that action. Movement is along the channels of least resistance.

---

[1] Les gisement de pétrole; L'industrie du pétrole en Roumanie; Ministére de Industrie et du commerce, 1910.

[2] The Diastrophic Theory, A. I. M. E. Trans., Vol. 56, pp. 733–753, 1917.

Diastrophic action is not sufficiently pronounced in many fields to be given such an important rôle. While diastrophic movements must certainly be considered as having assisted in causing and directing the movement of oil, gas, and water, it would seem inadvisable to consider them in any other rôle than that. Certainly the evidence does not warrant the assumption that they were the most potent factors in the accumulation of oil and gas.

Pressure in Oil and Gas Horizons.—The pressure under which oil and gas are stored varies from field to field and from pool to pool. Pressures as high as 2,000 pounds per square inch have been reported in California, but such pressures are not common. The records of the initial pressures in oil-containing horizons have not been taken in most of the pools so that it is difficult to give any estimate of the average of such pressures and their relation to other conditions. Many oil fields are so far removed from centers where gas could be sold that little or no attention is paid to it. In many cases in the past it has been permitted to flow wild for long periods. It is only in areas where the gas has a high market value that it has been carefully conserved and that gas wells have been closed in immediately after the sands were drilled into. Thus while numerous records of gas pressures are available, the number of cases in which the initial or first-day pressure of the gas is definitely known is not large.

The records in Table 45 show a progressive increase in the pressures of gas pools with increased depths. Generally speaking, the pressures appear to be equal to somewhat less than the weight of a column of water of height equal to the depth of the well. This has led to the suggestion that the pressure is due to the hydrostatic head. This is undoubtedly true in cases where the horizon containing the oil is continuously porous over wide areas and reaches the surface. The assumption that hydrostatic pressure is the cause of pressures in oil and gas sands leads to the theory that all pressures should correspond to the relative depths of the wells below the surface. This would mean, if the water were pure, a pressure equal to .434 pounds per square inch per foot of depth, or 434 pounds pressure in a well of 1,000 feet, 868 pounds in one of 2,000 feet, and so on.

Table 45.—Initial Gas Pressures in Representative Pools.

Pool	Sand	Depth in feet	Pressure in lbs. per sq. in.	Authority
Woodsfield, Ohio	Keener	1515	475	Mills & Wells; U. S. G. S. Bull. 693.
Woodsfield, Ohio	Big Injun	1468	500	Mills & Wells; U. S. G. S. Bull. 693.
Woodsfield, Ohio	Salt Sand	1295	280	Mills & Wells; U. S. G. S. Bull. 693.
Woodsfield, Ohio	Berea	2090	710	Mills & Wells; U. S. G. S. Bull. 693.
Butler, Pa.	Hundred Foot	1400	780	Mills & Wells; U. S. G. S. Bull. 693.
Butler, Pa.	Third Sand	1700	785	Mills & Wells; U. S. G. S. Bull. 693.
Butler, Pa.	Third Sand	1452	600	Mills & Wells; U. S. G. S. Bull. 693.
Butler, Pa.	Fourth Sand	1800	870	Mills & Wells; U. S. G. S. Bull. 693.
Butler, Pa.	Fourth Sand	1568	225	Mills & Wells; U. S. G. S. Bull. 693.
Butler, Pa.	Fifth Sand	1950	870	Mills & Wells; U. S. G. S. Bull. 693.
Cleveland, Ohio	Clinton Sand	2500–2900	800–1100	Rogers, G. S.; U. S. G. S. Bull. 661, p. 37.
Newberg, Ohio	Clinton Sand	3000	425	Van Horn, F. R.; A. I. M. E. Trans., Vol. 56, pp. 839.
Findlay, Ohio	Trenton Lime	950	400–450	Orton, E.; U. S. G. S. 8th Ann. Rep., p. 645, 1889.
Harve, Montana	?	947	490	Stebinger, E.; U. S. G. S. Bull. 641, p. 73.
DeSoto-Red River, Louisiana	Nacatoch,	725–975	300–350	Matson & Hopkins; U. S. G. S. Bull. 661, pp. 122–123.
DeSoto-Red River, Louisiana	"Oil Sand"	1660 below Nacatoch	700–1000	Matson & Hopkins: U. S. G. S. Bull. 661, pp. 122–123.
DeSoto-Red River, Louisiana	Deep Gas	150 to 200 below oil sand	1000–1200	Matson & Hopkins; U. S. G. S. Bull. 661, pp. 122–123.
Chickasha, Oklahoma	—	3178	1200	Brandenthaler & Campbell; O. & G. J., 5–20–'26, p. 110.
Panhandle, Texas & Okla.	—	Up to 3100	400 approx.	O. & G. J., 5–27–'26, p. 120.
Monroe, Louisiana	—	2275	1050	Bell, H. W.; O. & G. J., 2–4–'26, p. 58.

However, it is generally recognized that capillarity and friction prevent the full application of the hydrostatic pressure in any but the simplest forms of vessels. Furthermore, the water contained in oil and gas sands is not pure but has a variable percentage of salts. These tend to increase the weight of the water according to their nature and the percentage present. Thus the weight of a column of water one foot deep and one square inch in cross-section may be raised from .434 pounds to as much as .550.

Increased density and loss of effectiveness tend to balance so that the well not infrequently shows a pressure closely approximating that of a column of pure water of the same depth as the well. In other cases the variations from the pressures suggested by the theory are so wide that the value of the well depth as an indicator of pressure is open to doubt. In some cases the pressure is materially higher than the theoretical, in others lower. Not infrequently the pressure seems to correspond more closely with that which would be expected if the elevation of the lowest point of outcrop of the gas-containing bed had been used instead of the surface at the well as the basis of estimating.

Gas pressures can hardly be considered as due to present hydrostatic heads if the pressures of water, gas, and oil, do not increase proportionally with depths in the same well. It is not uncommon for a well to penetrate a water-bearing horizon, which completely fills the hole; and later, after drilling another thousand feet or more, to strike a second water-bearing horizon that is capable of filling the hole only a few hundred feet. The pressures under which oil is found vary with the individual pool and well much more than with depths of those pools and wells.

If present hydrostatic pressure be considered as the cause of the observed pressure in oil wells, it is difficult to reconcile the observed decline curve of the average well with the theory suggested. Certainly exhaustion of the oil and gas contained in horizons cannot have so rapid an effect upon the hydrostatic pressure of the whole horizon as is indicated when a gas well's pressure declines from a thousand pounds to less than a hundred, and an oil well, which had an original yield of several hundred barrels daily, becomes an insignificant pumper in a few months. Moreover, the decline of wells in horizons that are definitely known to be lenticular and not in any way connected with the surface is not materially different from the decline of wells producing from continuous horizons.

In all sand-producing horizons capillarity is apparently of major importance in restricting the movement of water behind oil and gas as they escape to the surface through wells. This is naturally most marked in the tightly cemented sands of low pore space. In the extremely porous sands, such as those of many of the pools in California, Russia, and the East Indies, the water follows close behind the escaping oil and gas and tends to fill up the pores and maintain the pressure. This tendency is even more marked in the porous channeled lime horizons of the Tampico-Tuxpam area of Mexico and of Maidan-I-Naftun in Persia. There hydrostatic pressure may be said to be truly the explanation of the pressure and the nature of the movement of the oil from the horizon.

As the sediments in most of the oil fields are relatively free from diastrophic movements at the present time, their pressures cannot be considered as due to present movements. As we have already seen that pressures do not conform to the depth of wells nor to the hydrostatic pressure that would be normal to those depths, we are forced to the conclusion that the pressures were developed in past time. This calls for an explanation not only of the origin of the pressure but of the means of preserving it as well.

Both explanations of the origin and the manner of preservation vary with the theory of the origin. Strictly speaking, the development and retention of pressure according to the gravitational theory depend solely upon hydrostatic pressure. In porous, unsaturated beds rising to the surface, there can be no pressure greater than the present hydrostatic pressure. In small porous unsaturated lenticular beds that do not outcrop and have never outcropped since their formation, there cannot be any true pressure upon the gas and only slight pressure upon the oil.

However, the reduction of the volume of the pore space subsequent to the accumulation of the oil according to gravity may bring the liquids and gases under compression. In addition, pressures may be considered as being developed by the expansion of the volume of the oil and gas through conversion of oil into gas under the influence of diastrophic agencies. If the evaporation of water be admitted, salts deposited may be considered as acting as cements to assist in the retention of the oil and gas in its original position during subsequent compacting and generation of gas. Unless there is considerable circulation of water after the accumulation of oil and gas, the amount of cement added to the sand from outside sources must be considered as of minor importance. In some areas such as the Valley Field of California, the reaction of the oil with the substances contained by the waters coming in contact with it has formed asphalt and tar seals capable of restraining considerable pressures.

The pressures developed by the capillary properties of oil and water are not definitely known. It is hardly probable that capillarity is responsible for the extreme pressures that occur in a number of oil fields. In some areas it may have been the cause of relatively low pressures. Capillarity may be given a much more important position in conserving those pressures through time. The inability of wells to extract more than a relatively small percentage of the oil contained in the oil horizon originally by ordinary methods is adequate testimony to the tenacity with which the oil is held by the minute openings in the rocks after it has once reached them. Water, having a surface tension three times as great as oil, must resist removal from minute pores of fine grained sandstones to an extent of which we have but little comprehension. In the production of oil from pools in which water under hydrostatic head surrounds the oil, capillarity prevents the water from pushing the oil forward and maintaining the pressure after the gas has been largely removed. Capillarity may be held responsible for the maintaining of pressures, despite the fall of the hydrostatic head, because of surface erosion for some time at least. Coupled with hydrostatic pressure it is capable of restraining the increased pressures developed in oil and gas horizons through compacting of strata and dynamic alteration of the oil.

In horizons in which the size of the pores is subject to wide variation, the force of capillarity acting through water should serve to isolate the different portions and preserve in each the pressures generated by other agencies. In compacting of such strata and of true lenticular beds, capillarity must be considered as of first importance in bringing such pressures into existence. Such pressures can be considered as directly proportional to the saturation of the original bed and the amount of the compacting.

According to the diastrophic theory, pressure is generated in the movement and is directly proportional to the resistance that is offered to the movement of liquids and gases by the strata themselves. Unless one of the agencies mentioned is utilized to maintain that pressure, it must necessarily become disseminated in all but lenticular beds. The hydraulic theory of Munn apparently depends mainly upon capillarity to preserve the pressures of the oil and gas pools after they have been formed but considers them as being formed either by capillarity or hydraulic pressure.

Summary.—From the evidence offered the writer feels that the gravitational theory must remain the basis of all theories of the accumulation of oil in reservoirs of commercial value. Its modification to suit the conditions in individual areas is in keeping with the differences in the geologic histories of those areas. It must be admitted that capillarity is important in causing the development of pay streaks in sections where strata are so nearly horizontal as to reduce materially the effective force of differences in gravity and where differences in porosity are sufficient to make capillarity an effective force. Similarly the action of gas in increasing buoyancy and decreasing the resistance to gravitational movement must not be discounted. Moving hydraulic water does not appear to be a satisfactory substitute for gravity as a controlling agency of concentration, but must be considered as an important agency causing circulation and directing the movement of oils and gases within porous beds to areas in which they may be permanently imprisoned.

Again, hydrostatic pressure would appear to be the underlying pressure in all fields. We must include, however, not merely the hydrostatic pressures now measurable in the fields but also the hydrostatic pressures that may have existed during periods when the beds were more deeply buried than they are today. While admitting the possibility of absolute dryness of many beds that produce oil and gas in other areas, the author is of the opinion that capillary water or lenticularity divides them from the producing areas. Even assuming dryness, capillarity would tend to maintain some pressure. The hydraulic pressure of Munn must be considered as being limited by, although not necessarily equal to, the hydrostatic pressures existing at the time of the circulation. Higher pressures than those postulated by hydrostatic pressures now in existence imply the retention of higher pressures produced by compacting and dynamic alteration of either the hydrocarbons or the strata containing them under the influence of capillarity or of cementing materials. Lower pressures in non-continuous strata, or in strata of varying porosity, indicate the inability of the full hydrostatic head to become effective because of the imperviousness of the beds surrounding the container rocks.

CHAPTER IX.

THE REPRESENTATION OF STRUCTURAL CONDITIONS.

Before the development of the gravitational theory of the accumulation of oil, structural mapping was of the most general nature. But with recognition of the great possibilities of obtaining production in the "highs," or upfolded areas, in contrast with the "lows," or basinal areas, came more careful and exact study of structural conditions. The technic of the petroleum field geologist of today is of much higher order than that of his predecessor at the opening of the present century. Similarly the methods of representing geologic conditions have been changed and improved. Today the methods of representing structure in oil fields may be said to include the following:

1. Actual photographs.
2. Surface geology maps.
3. Strike and dip symbol maps.
4. Contour maps, including surface and subsurface.
5. Cross-sections.
6. Stereograms.
7. Models—peg, plaster, etc.

The geologic structure of an area differs from its topographic character in that the latter includes only the physical form of the surface while the former includes the attitude of the rocks regardless of whether or not they are visible at the surface. In fact, geologic structure deals primarily with conditions within the crust rather than on its surface. Topographic and geologic structure may in some areas be quite similar. In areas of comparatively recent geologic origin the upfolds or anticlines frequently correspond with the ridges and hills. Similarly downfolds or synclines are likely to cover the same general areas as the topographic valleys. This relationship, one of value in reconnaissance work in many areas, does not hold where the rocks are older. Forces of erosion find the upfolded or mountainous areas much less resistant to their action than the synclinal valley sections and rapidly reduce them to the level of the valleys. Once so reduced, erosion finds that the systems of joints in upfolded strata are of much greater assistance to further weathering than those of the synclines. Thus, in Paleozoic horizons in which erosion has been active for many periods, the valley and the stream bottom are as frequently the indications of geologic "highs" as they are of "lows."

Photographs.—From this it may be deduced that the camera is not a very reliable geologic instrument for structural work and the photograph of a region cannot be depended upon to indicate its geologic structure. Exceptions to the rule are numerous, but usually the attitude of the underlying rocks is so obscured by inequalities in erosion and by concealing soils, either formed by weathering or deposited by surface agencies of recent activity, that the actual photograph receives but scant attention.

Surface Geology Maps.—While seldom used in the final location of test wells, the surface geology map forms the background for all of the more detailed work essential to the outlining of the exact form of the structure. The true surface geology map shows only one thing directly—the areas occupied by the rocks of the different geological formations. It is not primarily an instrument for showing structure. Yet in a broad way it is an excellent structural indicator. The broad basinal form of the western plains of Texas, Oklahoma, Kansas, and Nebraska, is clearly outlined. Similarly the gradual slope of the sediments in the coastal plain of Texas and Louisiana toward the Gulf of Mexico is almost as clearly indicated as it would be by a contour map. The geanticlinal uplift of the Cincinnati arch in eastern Indiana and western Ohio shows clearly on even the most general maps. The broad and high uplift of the Caucasus shows strikingly upon the geologic maps. In examples of this type the structural conditions outlined are of the broadest and most general character. They are so pronounced as to be clearly evident despite irregularities in topography.

With decreasing intensity and extent of the structural configuration, the topography takes on added importance. Even if the rock surfaces are exposed sufficiently to make it possible to outline the extent of the individual formations or their subdivisions with a fair degree of accuracy, the interpreter of the map must carefully consider the relationship of those outcrops to the topography in making his deductions. In regions of highly folded Tertiary and Cretaceous rocks, differences of a few feet in the vertical scale are not normally of great importance. The geologic folds, even where small in areal extent, are commonly of such intensity as to determine the character of surface rocks regardless of minor differences in surface elevations. In the more gently folded oil-yielding areas of the Paleozoic, even the most insignificant differences in surface elevations may serve to hide completely the most favorable structural conditions.

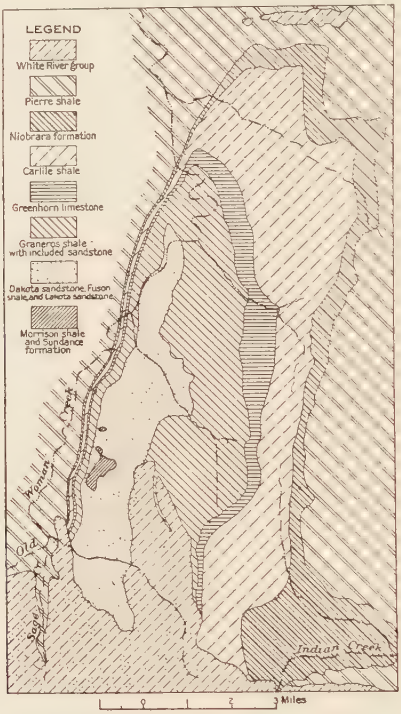


FIG. 34.—Surface geology map of a strongly folded anticline. An anticline on Old Woman Creek, Converse County, Wyoming. After Darton, N. H.: U. S. G. S. Bull. 691–A, p. 24, 1918.

In Pennsylvania and Oklahoma, oil and gas are frequently taken from structures whose closure—the vertical distance between the highest point of the fold and the lowest horizontal line which can be drawn in the same bed that contains the crest and still completely encircle that crest—is less than ten feet. In the Rocky Mountain Province, the structure that does not have a closure of at least two or three hundred feet is abnormal. Some having closures of more than a thousand feet have been mapped.

If all surfaces were perfectly horizontal, surface geology maps would be as good a means of location of test holes as the contour map.

Every outcrop that could be identified as being older than the rocks surrounding it would be a geologic high. Conversely, every outcrop surrounded by older rocks would be a geologic basin. However, the surface is not perfectly horizontal, and in sections like Pennsylvania, the outcropping older rocks may occupy the central locations and yet be the centers of synclines because of the slightly greater effectiveness of erosive forces there than in the areas surrounding.

Strike and Dip Symbol Maps.—The first improvement over the simple surface geology map came through the use of strike and dip symbols. The dip of a bed may be defined as the angle of inclination of the bed with the horizontal plane. It is taken at right angles to the strike. This may be considered as the line of intersection between the bed and the assumed horizontal plane. Strike and dip readings may be taken with fair accuracy where the dips are large; that is, above five degrees. Where the dips are only one or two degrees and

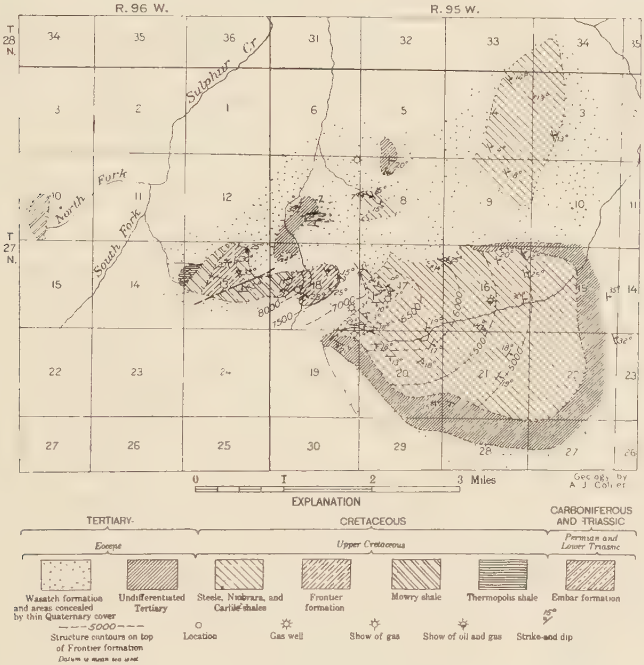


FIG. 35.—Map showing surface geology, strike and dip readings, and structural contours in the Buffalo Basin area, Fremont County, Wyoming. After Collier, A. J.: U. S. G. S. Press Notice, April 22, 1922.

differences are correspondingly slight, the accuracy of dip readings may be questioned. In sections where massive beds of rock show at the surface but in which individual beds are not continuous over a sufficient area to make it possible for the geologist to make definite identifications, the strike and dip method of mapping may be the only method which can be used. Dips are represented by arrows pointed in the directions toward which the inclined beds slope. The angle of the dip is usually marked on the map close to the arrow. A line perpendicular to the dip line represents the strike.

Strike and dip mapping has the element of rapidity in its favor. In sections where the dips are pronounced, a capable geologist can determine the outline of the structure with a reasonable degree of certainty. In all but the most gently sloping areas, it forms an excellent method of determining the sections that are worth more thorough examination. Errors of observation even in the most careful work tend to cast doubt upon the value of reports basing recommendations entirely upon such data. For this reason very few maps are drawn from strike and dip readings in sections of low dips.

Contour Maps.—In one sense every contour map may be considered as a subsurface map as it shows the attitude of beds below the surface as well as the position of the points of a selected outcropping horizon. In many cases the contour map includes the attitude of imaginary rocks. This usually means that portions of a bed are contoured despite the fact that they have been removed by erosion. This can be justified if their relationship to underlying beds, which have not been removed by erosion, is known.

The term "subsurface" is generally limited to the map constructed from data supplied by records of wells that have drilled to considerable depth. Between it and the true surface contour map of the geologist, which is based solely upon data observable in the field, is an intermediate type. This is based upon data supplied by shallow test holes that have been drilled or dug in sections which, for one reason or another, have been considered as of special promise but in which the surface data are not sufficiently conclusive to warrant final recommendations. Dug holes are naturally of limited depth. Drilled holes may be carried to depths of more than a thousand feet before a satisfactory prominent marker horizon is reached. Usually they are only two or three hundred feet in depth. The bulk of drilling of this sort is being done today with the diamond drill, but small churn drills have been used in some cases.

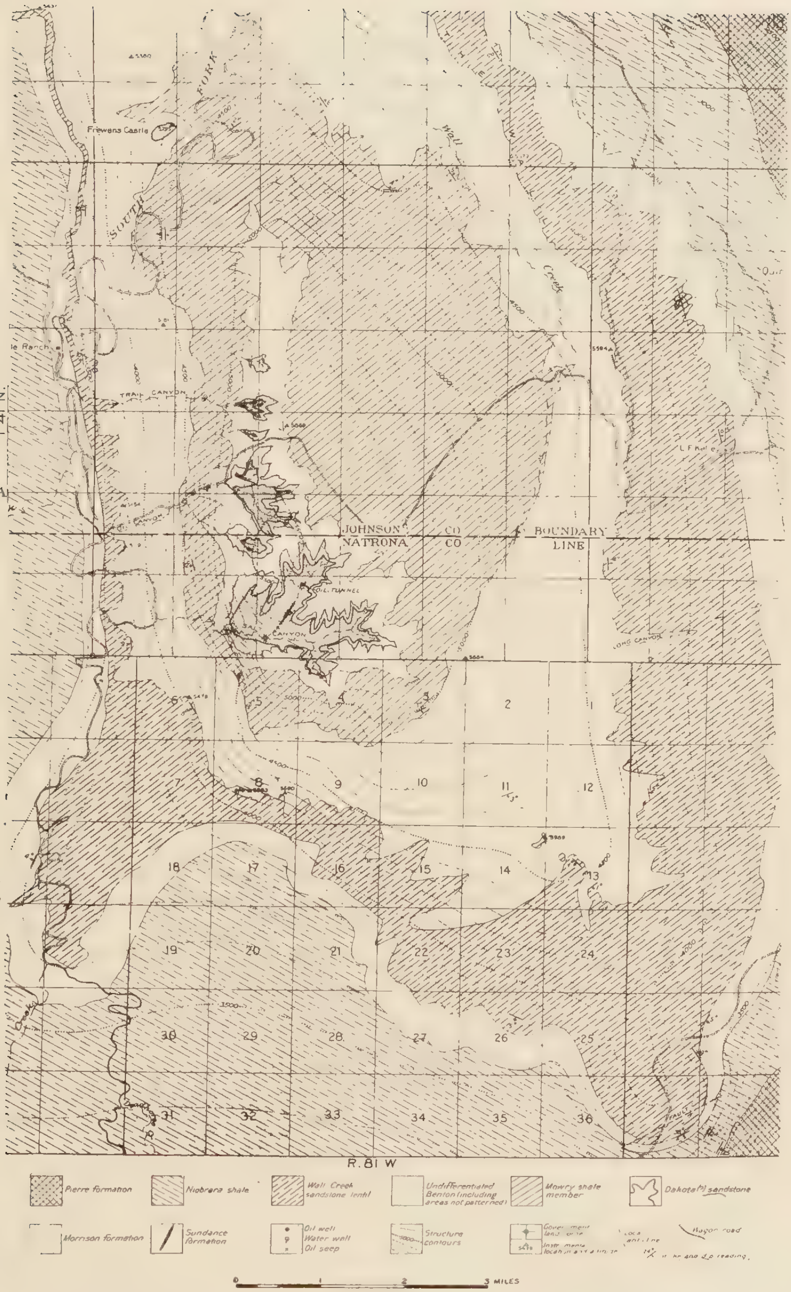


FIG. 36.—Map showing structural contours and areal distribution of rocks in the Powder River anticline. After Wegemann, C. H.: U. S. G. S. Bull. 471, p. 56, 1912.

Contour maps are constructed in the same manner regardless of the type of the data upon which they are based. The contour map may be called the topographic map of an individual bed. It may be the outline of the top of the bed, its bottom, or of some particularly prominent ledge in the bed. The exact part of the bed chosen depends upon the relative ease and accuracy with which observations may be made upon the several parts.

As in the making of topographic contour maps, it is impossible to connect all points of the same elevation because of the maze of lines resulting. Therefore all geologic contour maps are drawn on definite contour intervals. The most commonly used in areas of moderate and low dips is the ten-foot interval map. In this, lines are used to indicate differences of ten feet. Where dips are high, twenty-foot, twenty-five-foot, fifty foot, and even one hundred-foot, contour intervals may be found practical. The choice of interval is important. Maps drawn upon a hundred-foot interval in the Eastern and Mid-Continent areas of the United States would show very few of the structural conditions which determine the accumulation of oil in those areas. On the other hand, the ten-foot interval map is not needed in the Rocky Mountains, in southeastern Persia, or in the Valley Field of California. The data needed for such maps in these areas would call for extremely detailed work. In fact, it is doubtful whether, from the very nature of the strata and the abundance of places where outcrops are concealed by the soil, such a map could be drawn with any degree of accuracy. Certainly the map would call for the expenditure of time and money wholly incommensurate with its value.

Errors in Mapping.—The neatly drawn contour map often gives an impression of accuracy that is not warranted. Errors in such maps are of three types: errors of geologic observation, errors of mechanical observation and calculation, and errors of interpretation. The observations of the geologist are made upon outcrops of beds that are seldom continuous over a large area. The outcrops of the same bed frequently differ considerably at different points. Differences in lithological characteristics make it hard to identify individual horizons whose outcrops are not continuous. Marked variations in thicknesses within short distances make difficult the selection of corresponding points within the bed for observation. The exposure of a rock is the result of weathering. Irregularities in weathering, due to the less resistant character of underlying beds, may cause the bed that is being mapped to slump and assume abnormal positions. Such errors of observation decrease with care and experience, but absolute accuracy is practically impossible even in sections where outcrops are most favorable.

Errors of mechanical observation and calculation vary with the nature of the instruments used. The contour map prepared from data compiled by a geologist working with an aneroid can never equal in accuracy the work done by competent men with a plane table and an alidade. In turn, the plane table and the alidade are less accurate than the surveyor's transit. The refinement of the last is so high as to lead to questioning its desirability as a working instrument when the actual geologic observations may be three or four feet off. Greater refinement in observations calls for slower work and higher costs. As the use of the engineer's transit cannot remove the doubt as to the accuracy of the actual geologic observation, it seldom adds sufficient value to the observations to pay for the added cost. Because of this, observations made with the plane table and the alidade must for all practical purposes be considered as the standard for accuracy in petroleum geology. The map prepared from such data by competent men must then be considered as presenting the most accurate information possible.

Aneroid barometers are affected by changes in atmospheric conditions as well as by changes in altitude. Unless two barometers are used, one being kept at a control point and readings made at short intervals, the geologist is forced to return to a control point frequently to determine the extent of the atmospheric variation. In addition the barometer itself is not as accurate an instrument as the alidade. Where the country is sufficiently open to permit frequent and rapid returns to the control points, or the differences in elevations are great enough to neutralize the variation due to atmospheric conditions, the aneroid is a satisfactory instrument upon which to base the contour map. A somewhat greater range of usefulness is given where the control barometer is used or where the observer is able to check his observations with topographic maps covering the area in which he is working. In regions of low dips its value is largely restricted to checking in order to find major errors and to making traverses into places that can be reached only by the plane table with great difficulty and loss of time. In areas of moderate dip it is a satisfactory reconnaissance instrument, but even in such areas it is desirable to check the observations made by using the plane table outfit before the final map is prepared.

The personal element enters into all instrumental observations and calculations. Theoretically the personal error should not exist, but one must admit that it does. When a definite structure is outlined by a reputable geologist, he usually checks both observations and calculations so carefully as to reduce this type of error to unimportance before submitting his finished report. However, the locating of structures and the taking of leases is frequently hurried by competitive operations, and the desirable rechecking cannot be made.

Assuming that errors in geologic and instrumental observations and calculations are negligible, there remain the errors in interpretation. While the expression ''error'' is justified here in some cases, it should not be used in all. The geologist who fails to interpret adequate data correctly should undoubtedly be charged with an error in judgment. The geologic data available in most cases is meager compared with that which is desired and is really necessary before absolutely positive statements can be made. The limited number of outcrops and the wide spaces where no outcrops occur make it impossible for the geologist to determine the existence of minor flexures in advance of the drill. In attempting to reconstruct the picture of structural conditions, the geologist must depend upon his own experience and knowledge of the experience of others under similar conditions. Thus differences in the interpretation of the same data by men of high standing are frequent. Drilling may prove the interpretations of all to be wrong. Yet it is hardly fair to say that failures to make correct interpretations of incomplete data are mistakes which should be held against the geologist making them. However, this does not excuse the making of guesses based on evidence that is not sufficient to warrant logical interpretation.

The Columnar Section.—It is seldom possible in the making of a surface contour map to rely entirely upon the observations made upon the outcrops of one bed. Not only may one bed fail to show at the surface over a sufficiently large area, but there may not be a sufficient number of outcrops of any single bed in one area to make it possible to base the map upon that one alone. Thus the geologist may be forced to make observations simultaneously upon two, three, or even more beds, later resolving all of the observations into elevations on the bed upon which he bases his structural maps. In general the vertical distance between two beds is practically the same throughout the area mapped. The observation of that distance may be made easily where cliffs are high and practically vertical. It calls for considerable extra and difficult work where the country is relatively flat and the outcrops of the different strata are found at points at some distance from one another. The columnar section shows the relations

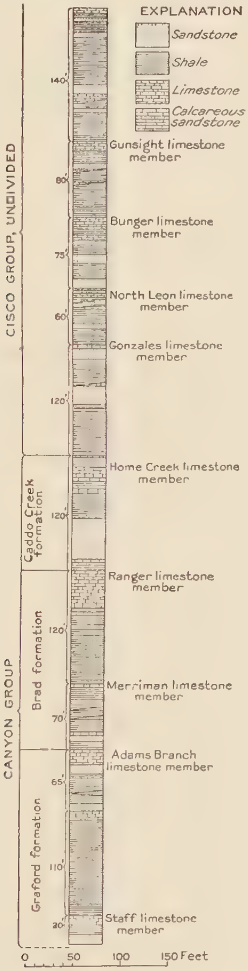


FIG. 37.—Columnar section of rocks exposed in the Ranger oil district, Texas. After Reeves, Frank: U. S. G. S. Bull. 736, p. 115, 1923.

arrived at and indicates the values that the geologist has used in making his contour map.

The columnar section of the surface geologist should be identical with the record of the well or test pit sunk at a point where the formations observed at the surface dip below the surface.

Well Logs.—The record of rocks penetrated by a well is known as the well log. Most wells are drilled primarily to reach the oil-containing horizon and to determine directly its value. An increasing number are being drilled to shallow depths to give information upon which more careful structural maps can be based, and to avoid deep costly failures, due to inadequate structural data. The logs of wells drilled by different methods vary greatly in value. The most desirable record is the one that is prepared by a competent geologist after

Table 46.—Rock Classification.*

General Class	Rotary-drillers' Term	Use in Rotary System	Cable-drillers' Term	Use in Cable-tool System	Technical Equivalent
Sands	Sand	Any uncemented sand.	Sand	Any uncemented sand; also many slightly cemented sands or very porous formations.	Sand
	Water sand	Sands, the samples of which appear clean and bright. Sands tested and found to produce water.	Water sand	Sands producing water.	Sand
	Quicksand	Sands that cave and settle rapidly.	Quicksand	Sands that cave and settle rapidly.	Sand
	Heaving sand	Sands that cave and are forced up the hole.	Heaving sand	Sands that cave and are forced up the hole.	Sand
	Oil sand	Sands or other porous formations containing oil.	Oil sand	Sand or other porous formation containing oil.	Oil sand
	Gas sand	Sands or other porous formations containing oil.	Gas sand	Sand or other porous formation containing gas.	Gas sand
Gravel, boulders	Gravel	Any formation havng the feel of gravel while drilling.	Gravel	Correctly used.	Gravel
	Boulders	Large locse pieces of any formation.	Boulders	Correctly used.	Boulders
Clay, shale	Clay	Clay or soft shale; usually not sticky.	Clay	Correctly used.	Clay, or sandy clay.
	Gumbo	Soft sticky clay.	Gumbo	Soft sticky clay.	Clay
	Shale	Formations having parallel bedding.	Shale	Consolidated clays.	Shale
Consolidated formations	Rock	Any consolidated formation.	Rock	Term not used.	Rock
	Gas rock	Any rock formation containing gas.	Gas rock	Term not used.	Rock
	Chalk rock	Applied to light-colored chalk only.	Chalk rock	Correctly used.	Chalk
	Sand rock sandstone	Terms used interchangeably for all cemented formation.	Sandstone	Correctly used.	Sandstone
	Packed sand	Loosely cemented sand.	Packed sand	Correctly used.	Sandstone
	Shell	Thin layer of hard material.	Shell	Thin layer of hard material.	Rock
	Shell rock	Any consolidated formation containing fossil shells.	Rock with shells	Formation containing shells.	Rock with shells
	Flint or flinty rock	Any very brittle rock.	Flint or flinty rock	Correctly used.	Flint
	Limestone	Limestone, also hard shale.	Limestone	Correctly used.	Limestone
	Lignite	All fossil wood.	Lignite	Correctly used.	Lignite or fossil wood
	Gypsum	Correctly used when recognized also reported as limestone or shale or sticky gumbo.	Gypsum	Correctly used.	Gypsum
Miscellaneous	Shells	Fossil shells.	Shells	Fossil shells.	Fossil shells

*After Knapp, A.: A. I. M. E. Trans., Vol. LXV, p. 428, 1921.

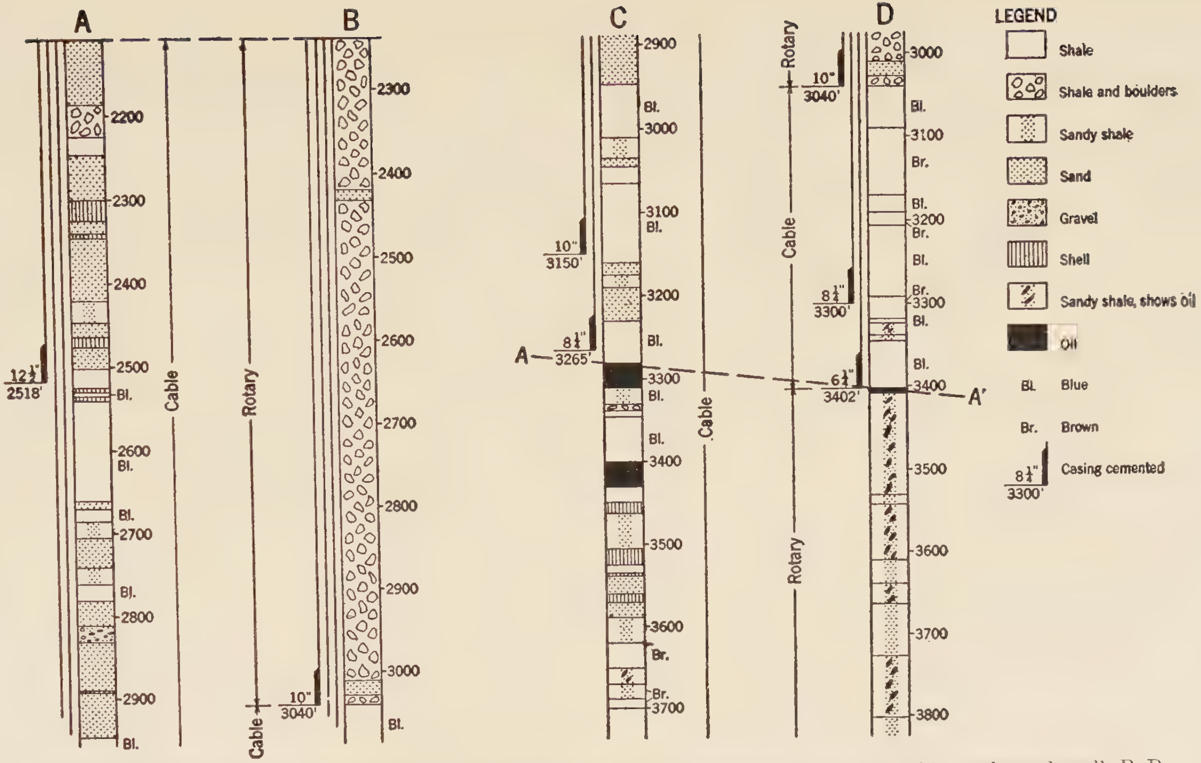


FIG. 38.—Graphic logs of two wells in a California pool well, A–C drilled with cable tools and well B–D chiefly with rotary tools. After Collom, E.: U. S. B. of M. Bull. 201, p. 69, 1922.

examination of the cores taken by a diamond drill. Steel shot drills furnish cores comparable in value with those of the diamond drill but have not been favorably received by oilfield operators because of the mechanical difficulties connected with their use.

The standard or cable drill is used in all areas where highly consolidated and cemented sediments must be penetrated. It is not entirely satisfactory as a geological instrument because it yields only cuttings for observation. From time to time a few hand samples are available. These are most frequently cavings whose exact depth is unknown and whose value is therefore questionable. Sometimes partly consolidated pieces adhere to the bottom of the bit, but the recovery of such fragments is not frequent enough to make them dependable sources of information. Unless contaminated by cavings the samples recovered by the cable driller do give considerable information about the rock that has been penetrated. Its composition may be determined by physical or chemical tests. The depth from which it comes may be determined within a few inches, if necessary. The feel of the drill and the wear on the bit give a good indication of the relative hardness and degree of cementation of the strata as a whole.

Logs of wells drilled with the rotary have never been considered as equal in value to those of the standard outfit. Instead of removing cuttings with a bailer, the rotary depends solely upon the flushing action of the circulating mud fluid. This means that the samples are not only thoroughly mixed with the drilling mud but arrive at the surface a considerable and variable period after the drill has passed through the formation. A careful sampler working with an interested driller who records every change in action of the bit can produce a reasonably accurate log. However it is never entirely satisfactory.

The greatest drawback in exploration with the rotary is the cementing action of the mud fluid. Mudding up of the walls of the well is absolutely essential to prevent caving. However, this mudding action tends to seal off oil, gas, and water. The location of water-bearing sands may be of no importance in most cases, but in some it is important to know this before attempting to shut out the water and test the oil horizon. Frequent failures to log oil and gas horizons, even when under substantial pressures, have caused the geologist to have little faith in the ordinary rotary outfit as a prospecting instrument.

TABLE 47.—COMPARISON OF DRILLER'S RECORD WITH GEOLOGIST'S DESCRIPTION. Part of record of well No. 4 of the Hope Water & Light Company drilled at Hope, Arkansas.*

Age and formation.		Depth at which sample was obtained.	Description of samples. (By H. D. Miser. No samples above 565 feet were preserved.)	Driller's record.		
				Material.	Thickness.	Depth.
		Feet.			Feet.	Feet.
Upper Cretaceous.	Bingen formation.	1,495–1,501	A drab-colored micaceous sandy clay.			
		1,501–1,585	Mixture in about equal amounts of micaceous sandy greenish-gray earth and micaceous calcareous glauconitic sand containing some small kaolinized feldspars here and there. There are a few small crystals of pyrite.	Shale, blue Gumbo Shale, sandy	30 10 45	1,530 1,540 1,585
Lower Cretaceous.	Trinity formation.	1,585–1,595	Mixture of drab clay with a smaller amount of red clay. Still smaller amounts of pyrite, quartz sand, and a few fragments of shells are present, but these are probably foreign.			
		1,595–1,610	Mixture of red clay, chiefly, with some sandy drab-colored clay and loose glauconitic quartz sand. All but the red clay are probably foreign.	Gumbo, red	20	1,605
		1,610–1,675	Main constituent is red clay; the minor constituents are drab-colored sandy clay, sand, pyrite, and lignitiferous matter. Three specimens of foraminifera were found.	Rock, hard Gumbo Rock, soft	10 35 25	1,615 1,650 1,675
		1,675–1,700	Fine angular quartz sand makes up most of sample, though there is some red clay and some dark clay. Three specimens of foraminifera found.	Rock, hard	25	1,700
		1,700–1,720	Drab-colored, slightly calcareous clay and some pieces of red clay.	Shale, blue	20	1,720
		1,720–1,735	This sample is so mixed that the character of the rock can not be determined. It consists of dark clay, calcareous gray sandstone containing abundant carbonized wood, red clay, pieces of limestone or shells, and much pyrite.	Rock, hard	30	1,750
		1,735–1,750	Sample consists mainly of brown fine quartz sand. Some pieces of sandstone having a calcareous cement are present. Some pyrite was seen. One foraminifer found.			
		1,750–1,758	Red and geenish clay, mainly red.	Gumbo	5	1,755
		1,758–1,780	Brown fine quartz sand with a little pyrite. Few pieces of red clay, and the other rocks are probably foreign. Some pieces of sandstone present.	Shale	25	1,780
		1,780–1,820	Gray fine angular quartz sand.			
		1,820–1,825	Pyrite abundant; one piece of woody matter partly replaced by pyrite; good many comminuted shells, much quartz sand, which makes up half of sample; and both red and dark clay.			
		1,825–1,835	Fine gray sand mixed with some calcite. This may be from a calcareous sandstone. There is one large piece of fossiliferous calcareous sandstone containing fine particles of disseminated pyrite. Some red and drab clay are present.	Rock, hard, white; salt water at 1,920–1,975 feet.	215	1,995
		1,835–1,852	Fine gray quartz sand and some calcite (probably calcareous sandstone). Very few pieces of dark clay present.			

*After Miser, H. D. and Purdue, A. H.: U. S. G. S. Bull. 691–J, p. 286, 1918.

In the last few years this has led to the practice of taking samples and cores with hollow bits in practically all important tests in rotary drilled areas. Coring now makes it possible to obtain a more complete record with the rotary than can be obtained with the cable tools. Core-taking devices have been materially improved in the short period since their value became recognized, but coring is still a slow and

TABLE 48.—GEOLOGIST'S LOG OF A PART OF A WELL DRILLED WITH A DIAMOND DRILL. Log of well on the Rutherford farm in central Illinois as interpreted by the Illinois Geological Survey. Data obtained from drill cores have been italicized.*

Sample No.	Description of samples	Thickness		Depth	
		Ft.	*in.*	*Ft.*	*in.*
1	Sandstone: Dark gray, shaly and micaceous, a red chert nodule (caving?) at 158 ft. 6 in.; calcareous hard nodule at 160 ft., with a similar layer 3 in. thick at 161 ft	5	2	162	
1a	Shale: Slightly sandy, gray, ⅛-*in. pyrite nodules* at 163 ft.; dolomitic, hard nodules at 165 ft. 9 in	4		162	
2	Shale: Gray, quite pure, *thin laminæ*, easily split into ¼-in. segments of core; dolomitic hard nodule at 165 ft. 9 in.; ⅙-in. *somewhat pyritic* band at 168 ft. 6 in.; ½-*in. brown (dolomitic and massive) band at 170 ft*	4		170	
3	Shale: Dark gray (*blue shale*), otherwise like No. 2; *a few slickensided surfaces* at about 174 ft.; *some dull brown bands* Ca ¾-in., harder and of less regular fracture than the rest	7	6	177	6
4	Dolomite: Brown, slightly calcareous and argillaceous, massive, like the ¾-in. bands of No. 3; *contains plant remains in fragments*, some pyrite grains and siliceous *pyrite veinlets*, with some galena	10		17[illegible]	
5	Shale: Dark blue gray, otherwise like No. 3; shows a few tiny fragments of fossils at 181 ft.; ¾-*in. dolomite at 183 ft. 7 in.; 3-in. dolomite at 186 ft. 6 in.; 2-in. dolomite at 184 ft. 10 in.; 2-in. dolomite at 185 ft. 2 in.; 2-in. dolomite at 185 ft. 6 in.; 2-in. dolomite at 186 ft. 7 in.; 1-in. dolomite at 186 ft. 10 in., irregular contact pyrite; 1-in. dolomite at 187 ft. 10 in.;* ⅛-*in. dark shale at base—a near-coal band* with some pyrite replacement of *plant remains;* 2 ft. 6 in. shale much darker gray, essentially black, broken by *1-in. dolomitic shaly band* at 187 ft. 10 in. (187 ft. 8 in. to 190 ft. 2 in.)	11	10	190	2
6	Shale: Dark gray, sandy and micaceous, with *interbanding* of thin, arenaceous lenses lighter in color	5	9	195	11
7	Shale: Dark gray, clean, probably grading in 3 in. to No. 8 (core misplaced from 197 ft. to 197 ft. 8 in.)	1	9	197	8
8	Shale: Sandy, gray, micaceous, with a few *more thin sandy lenses;* also dolomitic concretions (?) as noted: *1-in. dolomitic concretions (?) at 199 ft. 5 in.; 2-in. dolomitic concretions (?) at 199 ft. 7 in., pyrite veinlet; 2-in. dolomitic concretions* (?) at 199 ft. 11 in., graded from about 198 ft. to a pure shale at 201 ft. 7 in., *sharp contact* below	3	11	201	7
9	Sandstone: Dirty gray, micaceous, some *plant fragments carbonized*, shaly streaks *cross-bedded;* 6-in. band slightly lighter in color, no gradations above or below, slightly coarser at 205 ft. 0 in. to 205 ft. 6 in	4	8	206	3
10	Sandstone: Oil (left for detailed examination)	1	2	207	5
11	Sandstone: Light gray, shaly oily streaks *cross-bedded* in part, with some intricate *plications; minute shaly lenses*, darker and prominent	4	2	211	7
12	Sandstone: Oily (left for later examination)				
13	Sandstone: Shaly, light gray with darker gray shaly bands with *carbonaceous streaks, cross-bedded* in part; gradation below (like No. 11)	20	1	237	6
14	Shale: Gray, sandy micaceous, with lighter *sandy bands interbedded; minute plant fragments* rare; *breaks in part with smooth micaceous planes and in part with irregular fracture;* purer shale at 247 ft. 3 in.; *thinner* bedded dolomitic shale band at base; 3 in. *quite gritty*, 248 ft. 7 in. to 248 ft. 10 in	11	4	248	10
15	Shale: Gray, darker than sample No. 14, quite pure, *thin bedded*, shows no mica; breaks readily to ⅛-in. to ¼-in. bands but shows conchoidal fracture commonly; dolomitic in thin bands up to 1 in. from 251 ft. on; *one fern fragment and a few unrecognized plant fragments with a few flat bivalve shells or impressions;* some brown "*stains*" in flakes	7	9	256	
16	Shale: Black, carbonaceous but otherwise pure, readily splits to $\frac{1}{16}$-in. leaves; a *few plant remains*		5	257	
17	Coal: Clean coal 24 in., flakes of gypsum and pyrite infrequent; *charcoal parting* ⅛ *in.;* clean coal shale; *parting less than* ⅛ *in.;* clean coal 2 in.; *shaly parting* ⅜ *in.* (excluded in sample); *clean coal* 13⅜ *in.* (49 in.)	4	1	261	1
18	Clay: Greenish gray, brittle, fireclay, *abundant plant remains; slickensides throughout;* a little pyrite; thickness taken from driller's log, as the core was in fragments	10		261	11
19	Shale: Greenish gray, slightly lighter than No. 18; hard and brittle, calcareous, and containing numerous rounded masses like ⅛-in. pebbles, with some pyrite and coal *veinlets*				

---

* From U. S. B. of M. Bull. 243, p. 117, 1926.

expensive operation. The recovery of good cores demands frequent removals of the tools from the hole. This causes much delay. Longer cores will undoubtedly be obtained and longer runs made between pull-outs in the future as the core retaining and protecting devices are further perfected. At present the taking of rotary cores is usually limited to the coring of the zones in which oil, gas, or important water horizons are expected. The value of the log of the cored well to the geologist increases with the percentage of the hole cored. The production engineer is interested solely in the positions and characteristics of the water and oil horizons with which he must deal, but the geologist may find the foraminifera for which he is searching to establish the age of the productive beds in clays some distance from them. While the practice of taking cores has not developed to the same extent in cable drilling as it has in rotary work up to the present, such development may be expected to occur in the immediate future.

The value of the well log varies greatly with the character of the individual making it. The driller is primarily interested in making a hole, not in taking samples. Unless employed by a company in which the value of accurate records, even for dry holes, is fully recognized, the driller naturally feels that his future depends mainly upon his ability to make hole. Until recently and in some cases even today, the lack of cooperation between the geological and the production forces of a company present serious barriers to accurate sampling and give the driller added reason for devoting little attention to the taking of accurate samples and the keeping of good records. The logs of many wells, especially those of dry holes, are not only valueless but frequently lead to wholly erroneous deductions when taken in good faith by later investigators.

Cross-sections.—The accuracy of the log determines the value of all subsurface work. In its earliest form subsurface work consisted merely in comparisons of the depths to which wells were carried to reach the oil horizon. Very soon, however, the identity of the sequence of horizons in nearby wells was recognized; and comparisons of the depths of prominent marker horizons, as well as those of the actual producing zone, were made. Where the surface elevations were known to differ, allowances were made for those differences. These were first made by crude guesses or estimates but later were based upon surveyed casinghead elevations. As the number of records in an individual area became greater, the charted records of a series of wells, which formed a line across the producing area, were placed side by side and similar points connected. This formed a vertical slice or cross-section of a part of the productive area. By preparing several cross-sections in different directions, it was possible to obtain a fairly comprehensive view of the outline of the whole producing pool.

As the number of pools became larger and production was obtained from different types of horizons and at varying depths, the operator began to call upon the geologist to identify the individual horizons and to make estimates of the depths at which sands productive in nearby pools might be expected to occur. This gave the cross-section a much wider application and made necessary the use of records from dry holes as well as producing ones. Frequently, to increase the accuracy the geologist combined his subsurface data with that observed on the surface. In some cases he was called upon to link up his subsurface correlations with the outcrops of the same beds though they were many miles away. Within the individual pool errors of judgment in correlation are not common or serious; but where deduc-

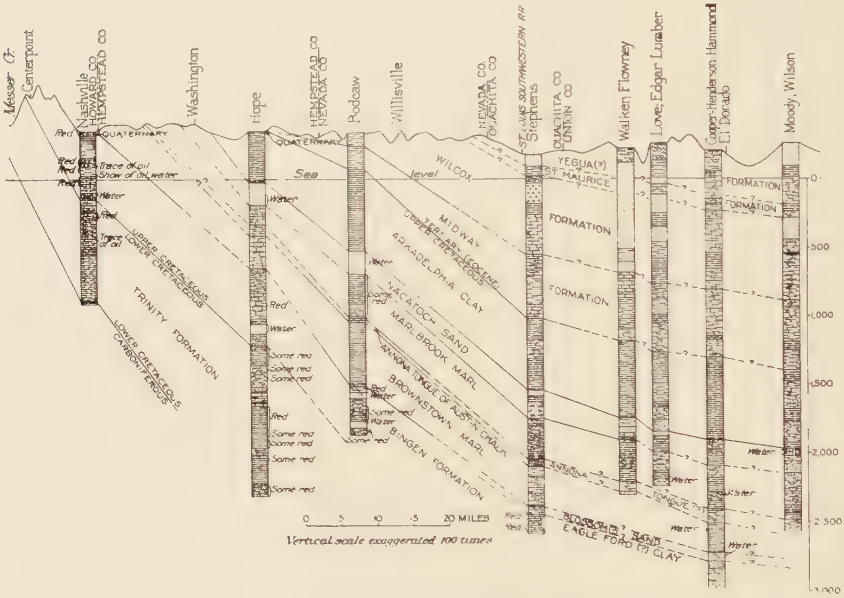


FIG. 39.—Cross-section of somewhat generalized records of wells from the vicinity of Center Point, Howard County, through the Elderado Oil pool, Union County, Arkansas. After U. S. G. S. Press Notice, April 22, 1922.

tions must be made from the records of single isolated wells, the chances of mistakes in correlation are great.

Subsurface Maps.—As the development of areas progressed, the cross-sections frequently showed marked variations from the parallelism of successive beds, which is the basis of the location of test holes from the data supplied by surface observations. While in a general way the surface contour map might be the same as that of the deep producing horizon, the existence of unconformities caused variations in the positions of the most favorable points for testing. In addition the distances between definite marker horizons showed mate-

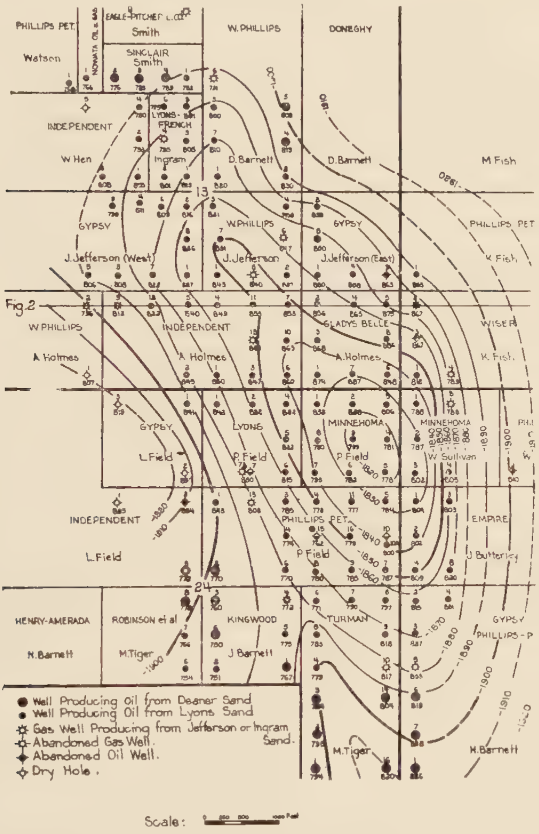


FIG. 40.—A Typical Subsurface Contour Map. Map of the Lyons-Quinn pool, Oklahoma. Contours drawn on the top of the Lyons oil sand. After Kirwan, M. J.: U. S. B. of Mines, Reports of Investigations, Serial No. 2612, p. 4, 1924.

rial differences in wells within short distances of one another. Therefore, whenever the number of records of productive wells and dry holes was sufficient, they were used in the construction of a contour map of the producing horizon or of some especially prominent bed close to it. In this way it became possible to avoid the chances of error arising in attempts to project the structural conditions through unconformities. The best possible map is naturally the map of the productive horizon itself or of some marker lying immediately above or below it. However, the records of wells to this depth are usually not available in sufficient number during the early stages of development to be of much assistance. Maps drawn on shallow horizons, which may have been tested in earlier exploration, while not entirely comparable with conditions in the lower beds, may serve to decrease the chance of error very materially.

The value of the subsurface contour map, like that of the surface, varies directly with the number of observations upon which it is based. This means the number of drill records that are sufficiently accurate and complete to be used. In general its applicability to the particular deep horizon that is being tested increases with the decrease in the vertical distance between the contoured bed and that horizon. This is not absolutely true in all cases as there are many instances in which there is no unconformity or irregularity in any of the beds between the surface and a point immediately above the prospective horizon. A single marked unconformity at that point will largely destroy the value of any horizon above it as a means of locating further drill holes. The only usable map is that of the productive horizon itself; the subsurface contours drawn upon other beds serve only to localize the position of the unconformity.

While the subsurface map cannot be considered as an absolute key to conditions below, it must be considered as an important agency in checking and improving upon surface data. The shifts in the positions of structural highs in inclined asymmetrical folds, the variations in intensity and position of faults, the lenticularity of many beds, and the uncertainties resulting from unconformities, all demand that the subsurface map or the cross-section be used whenever sufficient data are available. When production is known to come from lenticular sands or from points lying below an unconformity and usable data are available, reliance upon surface maps alone cannot be countenanced.

Convergence Maps.—In some sections the unconformities between surface beds and those yielding the oil or upon which it is desired to draw a contour map are reasonably regular. This usually means that no severe erosion or marked folding and faulting took place subsequent to the deposition of the lower bed and prior to the laying down of the upper. The unconformity is limited to the development of broad gentle folds or the tilting of the strata prior to the

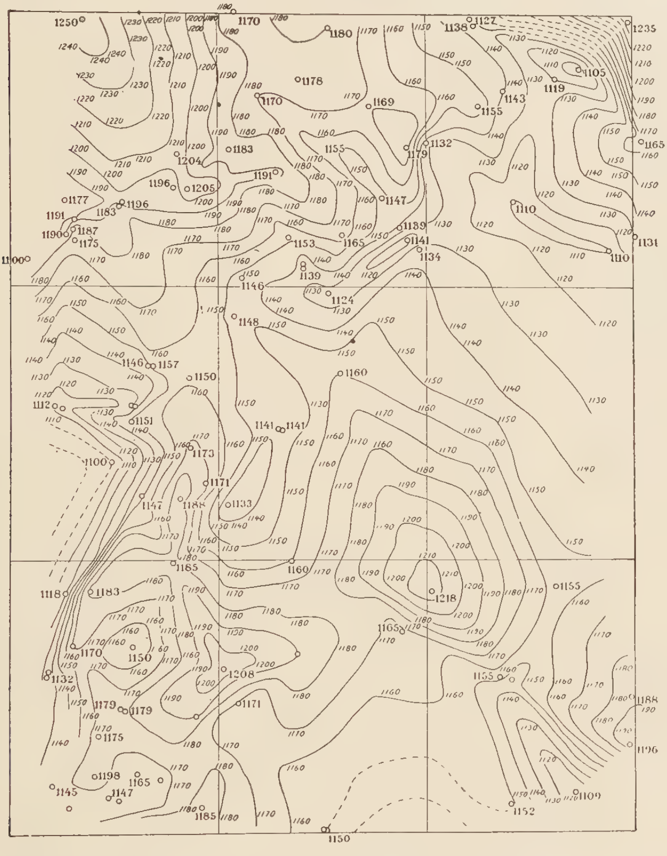


FIG. 41.—Convergence map showing variation in distance between the top of Vanport limestone member and top of Third or Gordon sand in the Foxburg Quadrangle, Pennsylvania. After Shaw, E. W., and Munn, M. J.: U. S. G. S. Bull. 454, p. 37, 1911.

deposition of the upper beds. In such cases the main period of crustal movement coming at a later date affects the two series of beds in much the same way. Careful examination of the records of a few wells penetrating both horizons may show the form of these gentle folds and the extent of the tilting to such an extent as to make it possible to map the variations in the interval between the beds and project the available data on the upper horizon through the unconformity.

A map showing the relative distance between beds is known as a "convergence map," and the lines connecting points of equal distance as "isochor lines." While the use of the convergence map to convert surface or upper horizon observations to elevations on a lower bed holds attractive possibilities, it tends to introduce possibilities of errors of serious nature. Unless the number of well records is large and the interval between the two horizons varies with extreme regularity, the returns are seldom commensurate with the risk of false interpretations.

Sand Maps.—The sand map cannot be considered as indicating structural conditions and should not, therefore, be included in this chapter. The growing recognition, however, of the importance of variations within the sand body upon the productivity of horizons has made it an important adjunct to the structural map and the cross-section. The sand map is prepared upon the same principle as the convergence map, the only difference being that the lines show differences in the thickness of the sand body instead of differences in the intervals between horizons. The lines of the sand map are known as iso-pachous lines.

The value of the sand map is widely recognized, but its limitations must be admitted. Such maps show only the thickness of the sand body; they cannot bring out the variations in porosity in its different portions. Moreover, they do not show the relationship of structure and sand conditions. Many maps are drawn that are combinations of structural and sand maps. These sometimes prove very helpful, but there is always the danger of confusion resulting from an excessive number of lines upon the same map.

Stereograms.—The data utilized in the preparation of contour maps and cross-sections can also be used in the making of stereograms. The value of the stereogram in showing structural relations to the non-technical man is generally recognized. It is not generally considered as a suitable instrument for the studies of the geologist or the production engineer. It cannot be drawn quickly and does not permit the placing of a large amount of detailed information upon a single sheet without confusion.

Models.—Plaster models are sometimes used to show the structural conditions in individual pools. The accurate construction of the plaster model involves considerable mechanical work. It is capable of showing more detail than the stereogram and like it, is much more easily understood by the layman than is the contour map. As a permanent record of the outline of a producing horizon for museum use or as the starting point for the class-room study of the invasion of salt water or of structural conditions, it is unsurpassed. To the technical man, who readily visualizes the data presented on contour maps, cross-sections, and sand maps, and who must deal with data that is being rapidly added to by frequent discoveries, its value is generally not sufficient to warrant its cost.

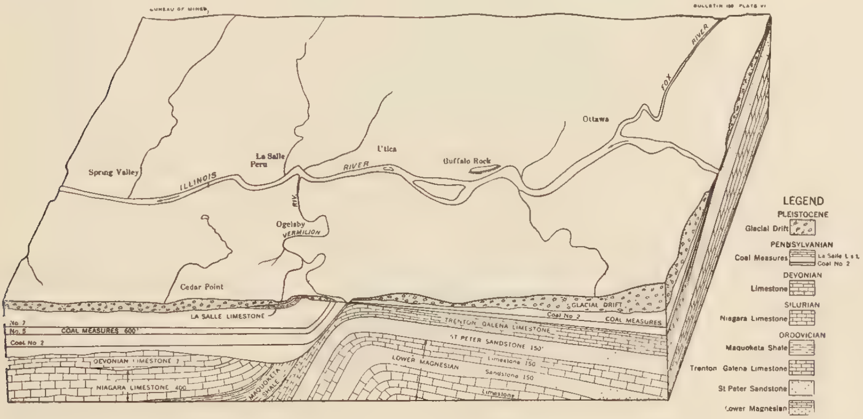


FIG. 42.—Stereogram of La Salle Anticline, Illinois, and Vicinity, showing the general geologic structure and stratigraphy. After De Wolf, F. W., Director Illinois State Geol. Survey, U. S. B. of M. Bull. 195, p. 50, 1921.

During the period of development it is frequently necessary for the geologist and engineer to think at the same time of conditions in several horizons. Proper perspective demands that all the data, whether dealing with structure, sand conditions, or water-containing horizons, be visible at one time. This can be done with fair success in the peg model. In such models individual pegs represent individual wells. Each one is colored or otherwise marked to show the positions of prominent key beds, oil and gas sands, or water horizons penetrated during the drilling. The correlation of the wells to bring out specific points can be done with strings. These can be removed later when other studies must be made.

The greatest value of the peg model lies in the ease with which it can be made to conform to new and changing conditions. Its greatest drawback lies in its bulk and lack of permanence.

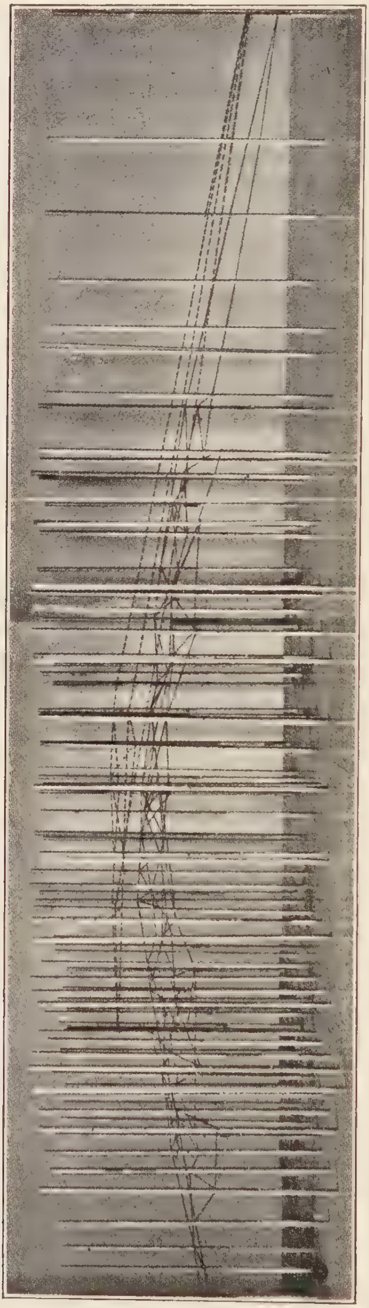


FIG. 43.—Peg Model of Coyote Hills Oil Pool, California. After McLaughlin, R. P.: U. S. B. M. Bull. 195, p. 48, 1921.

Summary.—In general the contour map appears to be the best method we have of representation of geologic structure in oil fields. It is far from ideal and must be used in combination with the cross-section and the sand map in many cases. But its use is not subject to the limitations that prevent the general use of stereograms and plaster models. It is not capable of showing the wealth of material that can be presented in the peg model, but its permanence and the ease with which the paper or linen map can be carried in a brief-case or attached to a report more than make up for this. The surface geology map is important in considering the geologic backgrounds of large areas but is generally not fitted to detailed considerations of structure. The strike and dip symbol map can be used with almost as good results in some areas as the contour map, but its sphere of usefulness is definitely limited to surface work in regions of high dips.

The contour map may be used for both surface and subsurface conditions. Its value, and the same is true of the other methods of presenting geologic data now in use, is dependent upon the character of the data upon which it is based and upon the skill of the geologist in interpreting that data. A considerable amount of space in this chapter has been devoted to discussion of the nature of errors that tend to decrease the value of geologic maps and sections. Such errors are not made willingly, nor are they the result of carelessness in most cases. They tend to decrease in number and importance as methods of collecting data are improved and the fund of previous experience gives a firmer base upon which to rest conclusions. The very nature of the conditions studied, however, makes it impossible to eliminate them entirely and forces the student to recognize that the interpretations he now considers correct may have to be revised in the light of later discoveries.

A SELECTED BIBLIOGRAPHY ON GEOLOGIC MAPPING AND THE REPRESENTATION OF GEOLOGIC STRUCTURES.

1. Cox, H. H., Dake, C. L., and Muilenburg, G. A., Field Methods in Petroleum Geology.
2. Dake, C. L., and Brown, J. S., Interpretation of Topographic and Geologic Maps.
3. Lahee, F. H., Field Geology.
4. Lobeck, A. K., Block Diagrams.
5. Hayes, C. W., Handbook for Field Geologists. (Third Edition revised by Sidney Page.)
6. Warner, C. A., Field Mapping for the Oil Geologist.

CHAPTER X.

THE NATURE OF OILFIELD STRUCTURES.

The accumulation of oil into pools of commercial importance demands that the rocks be of such character that they permit some horizontal movement of the oil and the gas. In areas of horizontal beds containing successive layers of impervious and porous strata, the oil and gas generated in the organic shales would tend to move into the porous layers. If these contained water, they would occupy the upper portions of each porous bed. But the ratio of oil and gas to water would be so small that they would be of no economic interest. While some horizontal movement might occur because of capillary action in sections in which the pore spaces were of different sizes, in most fields the drill does not indicate that such concentration has taken place to any great extent.

Wells drilled in aclinal areas (sections of no slope) show through their insignificant yields the necessity of segregation of oil and gas from water in some manner other than merely by vertical separation. The only alternative is horizontal movement. If we continue to adhere to the gravitational theory, such movement can only occur when vertical movement is taking place. The energy needed for horizontal movement must be considered as a component of the force which in an open container would be utilized in direct vertical movements. It follows that, other than movements through fissures, no vertical or horizontal movement can occur in beds that are not inclined. Inclination sufficient to permit the development of horizontal migration as a component of vertical movement is the first essential factor in the accumulation of oil into commercially workable deposits.

The movements of oil and gas in a porous inclined water-containing horizon would continue indefinitely if no barrier were interposed to limit that migration. The character of that barrier varies. In some places the porous oil-containing beds end abruptly at the face of a fault, where impervious shales prevent further migration. In others the porous rock gradually thins out or changes into an impervious one. In some cases the porous layer, while continuous, changes from one of sufficient inclination to permit migration to one which is so close to the horizontal in its position that farther movement is retarded, if not entirely prevented, by frictional resistance.

In the greater portion of the world's producing areas migration ends in the crests of domed or arched areas. Here the forces causing the movement of oil and gas are applied equally from all directions within the plane of the porous stratum containing these substances. As long as the beds above and below the porous container are impervious and prevent any direct vertical movement, there can be no migration of the oil and gas.

Sediments are seldom laid down upon perfectly horizontal surfaces. The extreme thickness of beds of similar characteristics in the centers of major geosynclines is definite proof of the continuance of subsidence during the periods in which deposition was taking place. Their gradual mergence with beds whose characteristics indicate that they were deposited in waters of shallow depths close to the shores is further indication that they were laid down upon a sloping bottom. While in many cases the subsidence was accompanied by block faulting, such action would not normally occur until after considerable tilting of the sediments had taken place. Coarse sediments laid down upon the tilted surface and covered over with impervious material would form ideal avenues for migration of the oil and gas that might be generated at a later date. The same action would be obtained if the tilting should occur during or after the period of deposition of the coarse sediments.

Where the porous strata resulting from the lithification of these coarse sediments have not been in contact with the surface through outcrops or fracturing since the generation of the oil and gas and their entrance into the porous strata, all of the conditions essential to the concentration of these substances are fulfilled. Accumulation under such conditions may be considered as resulting primarily from conditions existing during the period of sedimentation and may be traced directly to differences in physical characteristics of the deposited materials.

Where the porous layers are continuous over wide areas and have at any time since the formation of the oil and gas been in contact with the surface, the possibilities of the escape of those substances to the surface in the form of seepages are great. The existence of accumulations of oil and gas in such cases is dependent upon the development of local structural conditions that will terminate the movements and prevent the escape. This may mean concentration in true folds and incipient folds resulting from dynamic pressure. Many subordinate folds, in which oil and gas are found, are the result of inequalities in the settling of sediments. Faulting is a common phenomena accompanying both settling and dynamic movements. While less frequently the primary cause of oil accumulation, faults may be of major importance.

In some cases dynamic pressure manifests itself in direct vertical movements of igneous masses. In others it is indicated by the formation of massive salt plugs. Around and above both of these the sediments are frequently arched in forms which are favorable for accumulation. The porous portions of the igneous rocks may even contain oil and gas.

There are few pools in which the accumulation may be said to be entirely the result of only one of the agencies just mentioned. While folding may be the major factor in the forming of certain structures, drilling usually demonstrates that the concentration in areas equally well located with regard to the general structure has been materially modified by variations in the sand or by the positions of minor faults. Moreover, it should be remembered that modification and alteration of the physical characteristics of container rocks may have taken place subsequent to the original accumulation of the oil.

In discussing the different types of structures it would appear logical to take up first those whose formation is most closely related to the conditions existing during the period of deposition of the oil-containing sediments. However, the greater present economic importance and the greater availability of definite information make it more desirable from a practical standpoint to take up first the study of those structures which are the result of folding and faulting.

CHAPTER XI.

THE DEVELOPMENT OF FOLDED AND FAULTED STRUCTURES.

Before considering the form and character of the structures resulting from folding and faulting in the earth's crust, it is necessary to consider in a brief way a few things about the nature of the forces which cause crustal movement and the manner of their transmission through, and action upon, sediments. Basically, the activity resulting in the deformation of strata may be considered as being divided into two types. Under the first, would be included the deformation that results from the transmission of horizontal forces through the sediments. Under the second, would be included those structural developments that result from direct vertical uplift of the sediments. Ultimate analysis of the causes underlying both types of action may prove them to be fundamentally the same; but in considering the structural conditions of the upper portions in which oil and gas are found, the separation appears to be warranted.

Differential Compacting.—Compacting has undoubtedly contributed to the deformation of sediments. As originally laid down, they must have been highly porous. The porosity of unconsolidated clays and sands is probably decreased by one-half during compaction. The bulk of the compacting probably takes place very soon after the sediments are laid down. During this stage they are covered by a relatively small amount of overburden. Minor undulations in the sedimentary beds resulting from inequalities in compacting may arise and persist. It does not appear logical to believe that those minor folds will be duplicated in other sediments laid down at a later date. One would be more inclined to expect that later deposition would tend to fill in the irregularities and localize the minor foldings.

As the thickness of overlying sediments becomes greater, especially when it is measured in thousands of feet, the force tending to cause compacting becomes stronger. Any deformation that results may be expected to be more permanent. On the other hand, the resistance to compacting becomes more marked; and the actual reduction in volume in response to a given increase in pressure, smaller. At moderate depths such shrinkage becomes so small as to be considered as negligible in amount. Assuming that vertical shrinkage in sediments under cover is substantial, we are next called upon to discuss the possibilities and probabilities of the development of inequalities sufficient to produce measurable folds.

Such inequalities might be considered as resulting from differences in the original character of the sediments laid down in adjacent areas. V. E. Monnett[1] lays particular stress upon the irregularities in the degree of compacting caused by the existence of sand lenses in shales. As lenticular sands are seldom of great thickness, it is difficult to conceive of such action as accountable for more than the most minor deformation. However, in the absence of stronger folds, such minor folds may prove of major importance in the concentration of oil.

Where sediments are laid down upon irregularly eroded surfaces of already consolidated rocks, the possibilities of differential compacting become much greater. Differences might be expected to assume greater proportions if the irregular base was composed of crystalline non-compressible rocks, such as granites, marbles, or gneisses, rather than sedimentary beds still capable of some additional compression. Differential packing in all cases would vary primarily according to the size and form of the irregularities in the surface of the non-compressible base.

It does not appear probable that deformation would result from vertical compacting alone in areas devoid of irregularities in the basement rock surface or in the character of the materials deposited. It must be admitted that some restriction horizontally is to be expected with vertical compacting because of lessening of the linear distance occupied by the same arc in a smaller circumference. Irregular basins and elevated areas similar to those forming on the surfaces of slowly drying apples or other similar fruit might result from very marked vertical shrinkage. With the limited amount of compacting after lithification, it would appear probable that the greater part of the horizontal shortening could be accomplished by decreasing the space between the grains in the sediments.

There is, in the opinion of the author, no reason to believe that adjustments in the types of sediments found in oil fields would be of such degree as to cause buckling of beds. The importance of compacting lies not in the direct deformation of sediments, but in the preparation of the sediments for the application of other forces at a later date.

---

[1] Monnett, V. E.: Possible Origin of Some of the Structures of the Mid-Continent Oilfields, Economic Geology, Vol. 17, pp. 194–200, 1922.

If we disregard those structures which result from the direct uplift of sediments by the intrusion of igneous or salt masses, all structures must be considered as directly or indirectly resulting from inequalities in horizontal pressures. The direct connection is seen wherever the arched sediments can be shown to have been the ones that were capable of transmitting the horizontal thrust. The indirect types are those in which folded sediments visible at the surface or penetrated by the drill are of such nature as to make them incapable of transmitting the forces that were needed to fold them. Such folds must be considered as resulting from the vertical thrusts given by the arching of deeply buried rocks, which were capable of transmitting the horizontal pressures. Strata capable of transmitting forces are spoken of as "competent." Those which are capable only of reacting to the forces transmitted by other strata are called "incompetent." Vertical movement in strata such as occurs in folding implies the existence of vertical forces. Forces of such direction cannot be developed from horizontal ones unless the strata that transmit those forces are inclined. Beds approaching the horizontal in attitude are less subject to folding than those that are tilted. If the beds have been tilted irregularly or have been partly folded, the application of strong pressures may be expected to result in the development of pronounced folds whose form will in no small measure be determined by the condition of the beds at the time of application of the forces. Thus, while the tilting and folding resulting from unequal compacting can seldom be considered as the major factor in the development of oil-field folds, their importance in preparing the sediments for the application of dynamic forces is of the first order.

Nature of Crustal Deformation.—Willis[1] divides the zones of deformation of the earth's crust into four types: the zone of recrystallization or molecular flow, the zone of shear or mechanical flow, the zone of competent folding, and the zone of fracture. The structures with which the oil geologist deals originate in the upper zones of folding and fracture in many cases, but others must be considered as surface manifestations of much deeper conditions. Flowage by recrystallization involves the solution of the minerals and their redeposition with or without chemical change. It occurs only at considerable depth below the surface where the necessary high pressures and temperatures can be developed. Shearing is produced by major differential pressures upon highly compressed rock matter. It results in clear cuts or shear planes, which are independent of the original characteristics of the rocks affected, such as the form of pebbles or boulders contained and the positions of stratification planes. Shearing implies the existence of restraining pressures sufficient to prevent folding but the insufficiency of the pressures and temperatures necessary to bring about recrystallization. The action of different rocks in these two zones probably does not vary much because of the intensity of the forces that act upon them.

---

[1] Willis, Bailey: Geologic Structures, p. 144, 1923.

While there are no fractures, in the ordinary sense with which the term fracture is used, lines of weakness of far-reaching extent undoubtedly exist within the zones of shearing and recrystallization. Their downward limit may be considered as the upper portion of that part of the earth in which local fusion is the only means of causing movement in the rock mass. Where stresses are transmitted through the crystalline rocks of the shear zone, shearing along such lines is most pronounced. If parallel to the strike of the shear zone, only horizontal segmental movement may be expected to result from the application of differential pressures. If at an angle to the shear zone, the horizontal stress may be resolved into vertical stresses, which will cause vertical movement of one segment with respect to another.

Where the movement of the segments is severe, the shearing action is transmitted to the overlying beds within the zone of competent folding. Here it is naturally altered considerably. The horizontal movement parallel to the shear lines of the underlying mass may be converted into vertical movement in the upper beds. By this action the power of the thrust is gradually used up and the intensity of the effects materially diminished in the upper horizons. Such movement is torsional in character. The deformation of the strata resulting is entirely different from that resulting from forces which will be considered later.

The vertical movement resulting from stress perpendicular to the line of weakness may result in the elevation of block-like masses of considerable extent. The vertical movement may occur in two more or less parallel shear planes. It may take the form of movement in only one line of weakness and cause tilting of one segment with respect to another. In that case it might be expected to produce a form similar to the type that would be called a fault scarp on the surface. The vertical movement in either case would be materially altered in transmission through the blanket of overlying strata which obey the laws of the zones of folding and fracture.

The zone of shear merges into the overlying zone of competent folding. This is of variable thickness, both its upper and lower limits being determined by the character of the rocks contained in the individual areas. The lower limit may be considered as being determined by the ability of the rocks to support themselves in the form of an

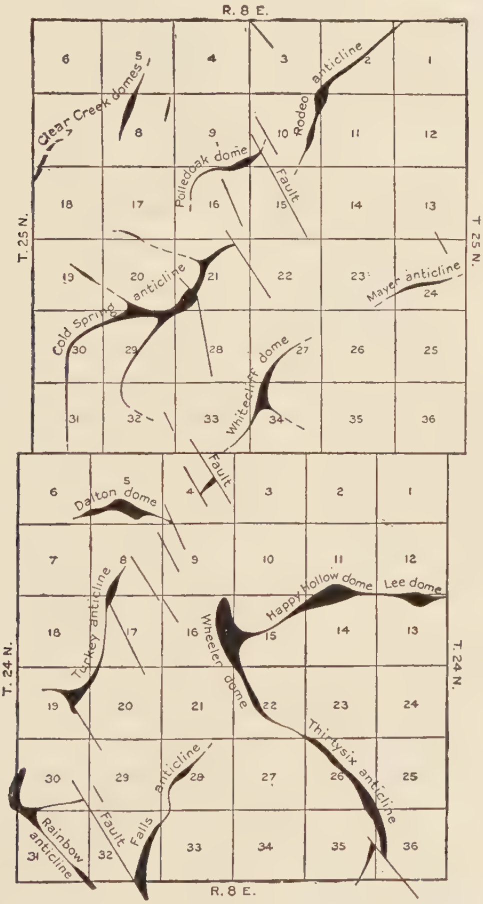


FIG. 44.—Map of part of Osage County, Oklahoma, showing irregular alignment of anticlinal folds and en échelon arrangement of minor faults. This is typical of northeastern Oklahoma and may be considered as the surface expression of movements in the underlying basement rocks. After Heald, K. C., and Mather, K. F.: U. S. G. S. Bull. 686, p. 156, 1922.

arch. The upper portion merges into the zone of fracture. In this the restraining influences are not sufficient to prevent movements of the pebbles and grains composing the rocks. Dynamic forces are largely taken care of by local or internal movements rather than by transmission through wide areas.

Competency of Rocks.—The development of arches requires that, the rocks be capable of transmitting the thrusts that are given them. The first quality required is that of rigidity. Limestone is an excellent example of a typically rigid rock. It is in direct contrast with shale or clay, which may be considered as flexible to the degree of plasticity. Rigidity is also possessed by sandstones and conglomerates. It is lacking in uncemented sands. Sandstones resist shearing because of their rigidity and grain characteristics; but unless bordering upon the quartzites, they do not have the power to resist fracture; that is, irregular breakage around the grains. Limestones are much superior in this regard. This is due to the smaller average size of the calcite and dolomite grains of which they are composed and the ability of intercrystal movements and local solution and redeposition to take care of minute adjustments, which would result in fracture in the coarse uneven sandstone. If fractures do occur in limestones as a result of unusual stresses, they are apt to be healed and the strength of the rock renewed by self cementation. Resistance to further fracturing is built up in this manner. In the sandstones, the fracture is likely to remain unhealed or become filled with a cementing material of low strength. A second period of stress finds the already formed fractures ideal avenues for further action of the same type.

In direct contrast to shales and, to some extent, sandstones, limestones are thickly bedded. They do not bend readily, nor do they fracture within the individual bed. Thus the limestone becomes the most competent type of sedimentary rock to control the development of structures. Sandstones, while important, are too apt to fracture to be of first rank. Pure shales are only capable of filling in and conforming to the positions given by the others.

Massive igneous rocks are theoretically incapable of converting horizontal forces into vertical movements except through shearing. However, even granites have some irregular cleavage or joint planes, which may serve in much the same way as the bedding planes in sedimentary rocks and permit the development of broad arches.

Horizontal Thrust Structures.—While some of the world's oil-containing structures must be considered as the results of direct uplift initiated below the zone of competent folding, the majority of the producing structures appear to the author to be more probably the products of horizontal movements within that zone. These movements are closely allied to mountain building action. The major mountain systems have resulted from the folding of sediments deposited in synclinal basins. Such folding varies in intensity with the proximity of the original land mass from which the sediments were derived or of other highly consolidated and usually crystalline rock masses. The appearance of the successive folds in the sediments and the marked shortening of the crustal area occupied by them would indicate that the sediments have been compressed by forces pushing outward from such masses. The sediments contained in the Appalachian Mountains, if laid out horizontally, would occupy a belt forty to fifty miles greater than the width of the present mountain belt.

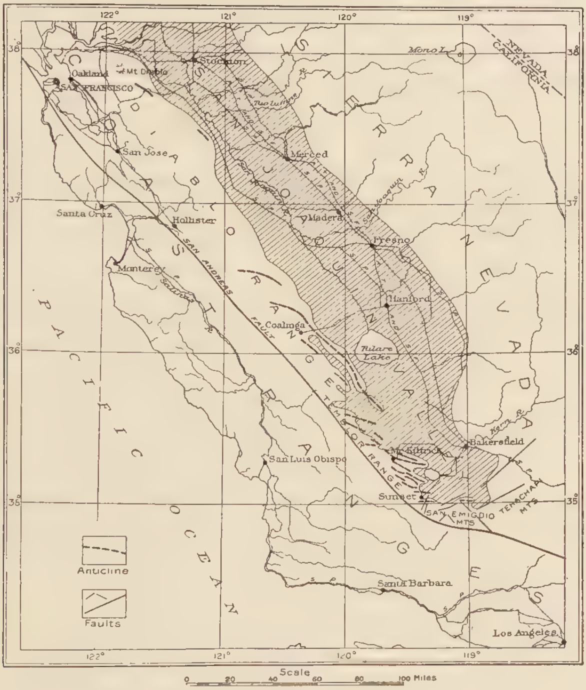


FIG. 45.—Sketch map showing position of chief anticlines and major faults along the west border of the San Joaquin Valley. After Pack, R. W.: U. S. G. S. Prof. Paper 116, p. 56, 1920.

Similar figures can be given for the Coast Range of California, for the Alps, and other folded mountain systems. The discussion of unsettled questions concerning the exact reasons for the development of the tremendous pressures necessary for such intense folds is beyond

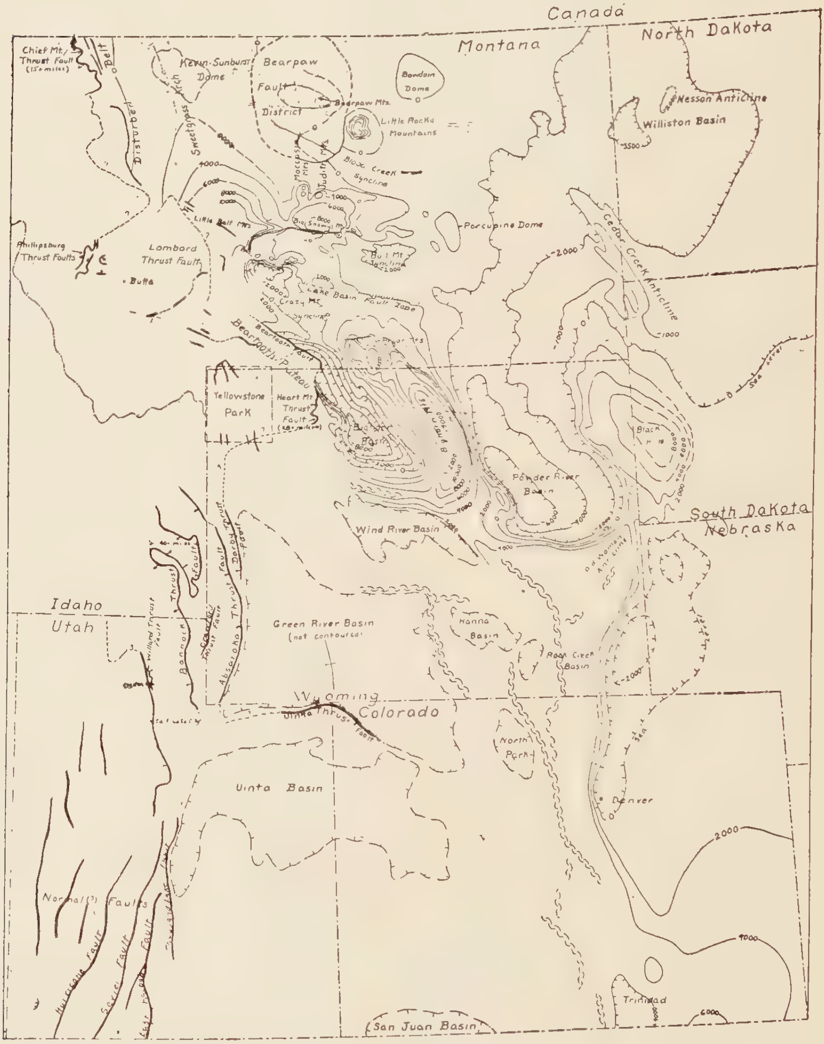


FIG. 46.—Structural sketch map showing position of major structural features of the Rocky Mountain Region of the United States. After Thom, W. T., Jr.: A. A. P. G. Bull., Vol. 7, p. 3, 1923.

the scope of this volume. Great folded systems are not known as containers of commercial quantities of oil or gas. However, their close connection with less intense folds, which do contain these substances, lying farther from the source of the thrusts is so evident that their relationships and origin are of extreme importance to the petroleum geologist.

Where the basins of deposition are large and fairly deep and the period of subsidence and deposition long, the thick beds of limestones form excellent trusses through which to transmit the compressive forces. In such areas the earlier sand deposits may be largely cemented before the inception of the major period of orogenic movement. The strength of the truss tends to the development of a wide belt of folding. The individual folds are apt to show a definite but gradual gradation from major or mountain folds to minor folds of comparatively small extent. A typical example of such a basin is the Appalachian geosyncline, which was mainly an area of subsidence and deposition throughout all of the Paleozoic, and was subjected to thrusts that caused mountain building action during the last part of the era.

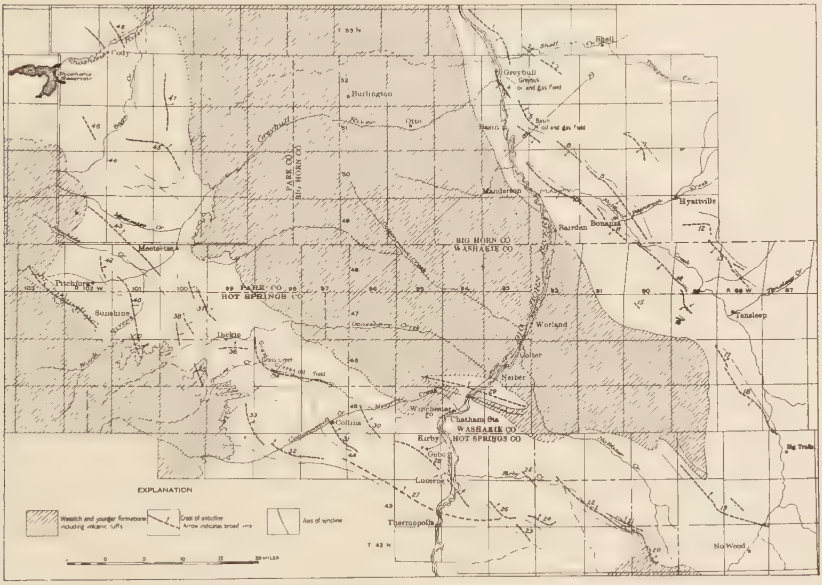


FIG. 47.—General Map of the southern part of the Big Horn Basin showing position of more important anticlines around edges of basin. After Hewett, D. F., and Lupton, C. T.: U. S. G. S. Bull. 656, 1917.

In the comparatively deep narrow troughs of short life in which much of the Tertiary and Mesozoic sediments were laid down, the limestone was of minor importance. Deposition was extremely rapid and cementation barely initiated when dynamic forces were applied. Such areas are characterized by narrow belts of intense folds, which die out rapidly within a short distance of the center of the compressive action. The Valley Field of California, producing from a narrow belt of large folds roughly paralleling the still larger folds of the Coast Ranges to the west, is typical of this group. The general absence of similar folds of smaller proportions toward the center of the basin and away from the Coast Ranges is indicative of the incompetency of the great thickness of unconsolidated and lime-lacking sediments to transmit the forces developed. In a somewhat similar manner, though numerous folds having closures of more than a thousand feet border the rims of the Big Horn Basin in Wyoming and parallel the mountain ranges surrounding it, the sediments in its center show little indication of the intensity of the forces that have been operating in close proximity to them.

Direct Uplifts.—In some cases the intense folds parallel to mountain folds may be considered as surface manifestations of vertical shearing in the underlying crystalline base. It would seem necessary to assume that shear movements in the basement crystalline masses are responsible for the development of uplifts of regional importance; such as, the Cincinnati Arch of Ohio, Indiana, Kentucky, and Tennessee; the Bend Arch of north central Texas; the Marathon fold of western Texas; the Sabine uplift of Louisiana and eastern Texas; and the Sweetgrass uplift of Montana and southern Alberta. These folds differ from those resulting from direct horizontal compression to so great an extent as to leave no doubt as to differences in origin.

The Cincinnati Arch would appear to be an area of uplift occurring as a direct reaction to the down dragging action caused by the deposition of immense quantities of material in the Appalachian syncline to the east of it and in the less definitely outlined basin to the west. Similarly the Sabine uplift may be considered as a reaction to the down dragging caused by deposition of material derived from the mountainous areas of central Texas and the southern Appalachians in the sections immediately southwest and southeast of it.

Explanation of the occurrence of large, sharply outlined, anticlinal folds in areas where similar folds are lacking is more difficult. Two of the most important producing folds in the world, the Cushing

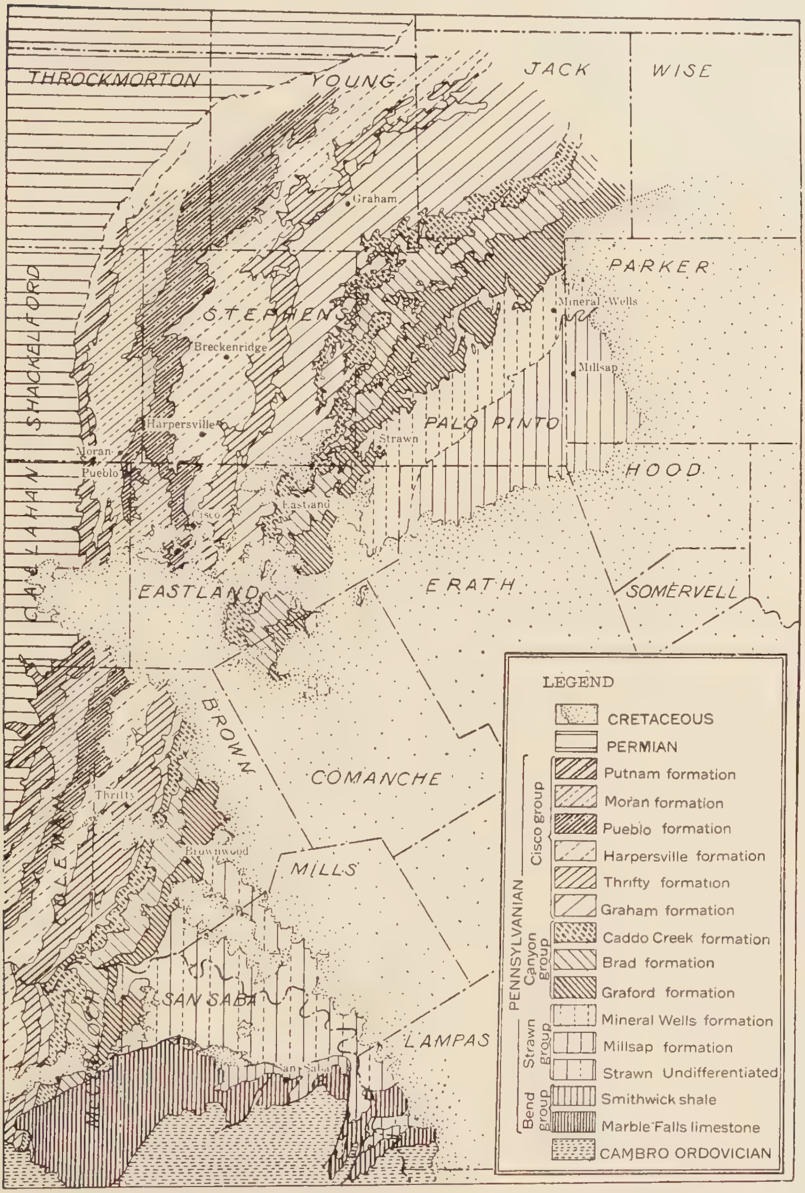


FIG. 48.—Map showing areal geology of a section which has been subjected to uplift and tilting. Formations in North Central Texas. After Moore, R. C., and Plummer, F. B.: Jour. of Geol., Vol. 30, p. 27, 1922.

anticline of Oklahoma and the La Salle anticline of eastern Illinois and southwestern Indiana, are of this type. One may consider such folds to be the result of vertical movements along planes of weakness in the shear zone. In that case their origin would be considered as somewhat related to that ascribed to the larger regional uplifts, excepting that the movement in the shear zone would be restricted to movement along one plane rather than taking the form of "horst" action.

Such uplifts also may be considered as resulting from the development of vertical forces from horizontal forces transmitted for long distances through deeply buried and nearly horizontal strata. The absence of tilting in the area between the strong fold and the center of the thrust would retard the development of folds in that section. The strength of the Cushing fold may be considered as resulting from the ability of the beds, which had been partly tilted by differences in compacting, to convert the horizontal stresses into vertical movement. Inasmuch as it has been proved that the Cushing fold is located above an earlier topographic ridge, this explanation would receive considerable support in this case at least. Another possible explanation is that of the intrusion of igneous matter through a plane of weakness, the flow not being of sufficient size to manifest itself in the upper crust in any other manner than through the development of a laccolithic uplift of the existing sediments. The absence of indications of igneous activity in the areas adjacent to both of the major folds named make this explanation rather improbable in these two cases.

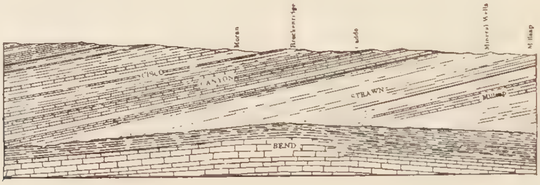


FIG. 49.—Diagrammatic sketch across the Bend Arch, North Texas, showing the broad character of the uplift in the underlying beds and the marked unconformity between them and the upper horizons. After Moore, R. C., and Plummer, F. B.: Jour. of Geol., Vol. 30, p. 23, 1922.

Where movements in the shear zone are entirely horizontal in character, the intensity of the movements necessary to the development of folding is great. The movement of one segment with respect to another along a plane of weakness between the two shows the moving segment to be under great pressure, but also indicates that the movement is opposed by a force which is capable of neutralizing it in the non-moving segment. Where shear zone segments move parallel to the lines of weakness, the torsional strains developed in the overlying beds are, for the most part, small. The transference of the movement of the shear zone into movement in the upper strata depends upon the absence of bedding planes and other planes of weakness, which would tend to absorb the forces in sliding. The thickly bedded limestones have a minimum of such planes and are therefore not capable of making much adjustment in this manner. On the other hand, shales may absorb practically all of it. The action of sandstones will be intermediate in character. In thickly bedded limestones the horizontal movement of the shear zone may be converted into vertical arching at relatively great depths below the surface.

The amount of vertical movement in the limestone must be considered as varying directly with the thickness and character of the rocks above it. If the strata above are composed largely of competent beds, the arches may attain considerable height and also extend for some distance horizontally. If, however, the upper beds are largely incompetent, the weight of the mass sustained by the arch tends to restrict its size. Where the beds are all competent, there should be only slight differences in the amount of vertical movement in different horizons. Where competent beds are overlaid by incompetent ones, the intensity of the movement in the upper strata will be found to be considerably less than in the lower.

Causes of Faulting.—Faulting of strata is frequently considered as indicating the existence of stresses within the crust too great to be relieved by folding. This is strictly true only when the faults involved are of the reverse or compressional type. The normal or tensional fault is commonly an indication of the inability of beds to produce folds because of incompetency. The strata tend to fracture rather than bend because of their lack of cohesion, inability to heal themselves by recementation, or the absence of the homogeneity of composition needed for intergranular adjustments throughout the beds as a whole. Normal faults are commonly associated with vertical uplifts in incompetent beds. The incompetent beds are not only unable to support themselves but also lack the cohesion necessary to maintain contact between the centers of uplift and neutral areas surrounding them. Such faults may be initiated in shales or even in clays but in the latter are apt to be extremely small as the absence of strength prevents the building up of any appreciable strains within them before sliding begins. The lack of homogeneity in sands and conglomerates tends to permit the building up of some tensional force before the slipping begins. It further tends to restrict slipping to movements along the plane in which the first movement takes place. Because of their strength well cemented sandstones permit the building up of large tensional forces. This tends to delay the fracturing, but the brittleness and lack of healing qualities tend to accentuate the action when it does occur.

Extent of Faults.—Fractures formed in this manner must be considered as purely surface phenomena. They are caused by deep seated movements, but they themselves die out within relatively shallow depths. Competent limestones lying between easily fractured sandstones tend to resist the fracturing action until tensional forces are built up to a degree greater than the strength of those limestones. It follows that in response to similar forces the number of faults in limestone areas will be less than the number in sandstones; but, that when fracturing does occur, the faults will be of greater intensity. Unconsolidated clays and shales tend to absorb the fractures and convert them into internal adjustments. Where there are considerable thicknesses of shales or thinly bedded sandstones, the fault plane is frequently changed from a vertical plane to one that is almost horizontal by adjustments of the stresses by movements along the bedding planes. Though individually small, the sum of all of the adjustments made in this way is sufficient to reduce both vertical and horizontal components of the fault movement to nothing within relatively short distances.

Normal tensional faults are not in all cases to be considered as strictly superficial phenomena and of only local importance. The Balcones fault zone of Texas, in which normal faults separate the rising northwest areas from the sinking areas to the south and southeast, must be considered as far deeper in origin than ordinary faults. The downthrow of this group of faults is to the east and amounts to as much as a thousand feet. The Mexia-Luling system of faults occurs thirty to forty miles east of the Balcones faults and shows a displacement of two hundred to five hundred feet but with the downthrow on the west side. Drilling along the latter has definitely shown that the intensity of the fault does not decrease with depth but even shows a material increase. In some places according to Lahee[1] the fault shows four to five hundred feet of displacement in the Austin Chalk of Cretaceous age and only one hundred to one hundred and fifty feet in the overlying Midway formation of the Tertiary.

---

[1] A. I. M. E. Trans., Vol. 71, p. 1340, 1925.

Several interpretations have been placed upon this increase. The essential point is that the fault does not die out but increases as it goes toward the zone of competent beds. The explanation of such deep seated tensional faults may in some cases lie in such severity of the vertical movements in competent beds of the limestone type as to cause faulting in the same manner as it is accomplished in the brittle sandstones. In the absence of indications of folding of the strata, which would normally indicate intense deformation, it would appear more logical to consider that the faulting in these two areas is a direct representation of vertical movements in the shear zone. That these movements have not been converted into folds may be attributed to the absence of a sufficient thickness of competent strata between the crystalline base and incompetent upper beds.

Normal faulting, even when of deep-seated character, implies no decrease in the areal extent of the strata affected. In reverse faulting the upthrown segment passes above the downthrown one and the area of the beds is therefore decreased. Reverse faulting is, therefore, common in those areas which are under compression. Faults of this type are frequently called compression faults. In a broad sense this is true, but it must be recognized that the actual fracture occurs only after some attempt at folding and is due to excessive local tensional stresses.

The compressional fault cannot be produced by any other force than horizontal pressure. While such faults may be developed in the less competent beds, they seldom reach major proportions unless originating in beds capable of developing major stresses. The reverse fault in a series of incompetent beds may be considered as an indication of a similar condition or of intense folding in the competent beds below.

The angles made by the fault planes in compressional faulting vary widely. In some cases the angle is so close to the vertical that it is difficult to determine whether the fault is of the normal or the reverse type. In others the plane is nearly horizontal. It is a reflection of the direction of easiest fracturing and of the amount of deviation of the force from the horizontal by combination with vertical forces.

The development of faults as against folds is probably in a large degree traceable to the time element. Where the force is built up slowly, adjustments within the beds tend to heal the incipient fractures. Where the force is applied suddenly, this cannot take place.

Summary.—Deformation in strata cannot be traced to one cause alone. Horizontal forces are almost invariably accompanied by vertical movements. Where the period of deformation is long continued and in part simultaneous with periods of deposition, the resulting structures are complicated by the laying down of sediments of varying thickness upon those which have been partially folded. The later sediments are naturally subjected to less deformation than the earlier ones. Where periods of deformation are intermittent, erosion may further alter the forms. Minor tensional faults are probably present in practically all folded structures. In some they are of sufficient size and so located as to be of greater importance in determining the areas of oil accumulation than is the major fold itself. Similarly fault line accumulation is frequently altered by the action of folds that accompany the faults.

While the structures that have been studied by petroleum geologists may be placed in a relatively small number of groups, the conditions in no two structures can be considered as identical. Each one is the result of a combination of forces acting in different ways to produce a result which will differ in some way or another from all others.

A SELECTED BIBLIOGRAPHY ON STRUCTURAL GEOLOGY.

1. Leith, C. K., Structural Geology.
2. Willis, Bailey, Geologic Structures.
See also bibliography on page 114.

CHAPTER XII.

CHARACTERISTICS OF FOLDED STRUCTURES.

The anticlinal fold produced by horizontal compression or by vertical uplift should be equal in length to the distance along which the pressure was applied. Actually individual folds are not continuous through long distances. The forces tending to cause folding commonly produce a series of folds that arrange themselves more or less en échelon to one another. Each individual fold is referred to as an anticline or syncline according to whether the strata are folded upward or downward. The vertical distance between the highest point in any particular bed and the lowest horizontal line which can be drawn in that bed so as to completely circle the crest is known as the closure of the anticline. Although less commonly used, the term may be applied also in measuring the depths of synclines.

If the strata were arched upward by a vertical thrust applied through a single point, the resulting fold would probably have a definitely domed form. The crest or highest portion would be a single point. Where the fold is the result of horizontal pressures acting parallel to each other, the crest developed is not a single point but is elongated into a line. This is roughly at right angles to the direction of the lines of pressure. The true crest line would include only points of equal elevation. Its length in most cases would be comparatively short. If this line were extended to include the full length of the fold, it would be called the axial line. Except at the ends of the fold, the direction of the dip of the bed folded up in this manner would be nearly perpendicular to the strike of the axial line.

The crests and axial lines in different beds in the same fold may be directly below each other. The vertical plane which would contain all such lines is known as the axial plane. The fold itself would be called an upright fold.

The term "axis of a fold" is sometimes used with reference to the axial plane and again with reference to the axial line. In the case cited there is no importance in making a distinction between the two, but in most cases the axial lines and the crests of the different beds are not directly under each other. The plane containing them would be an inclined one. In some cases it would not even be a true plane but a curved surface.

Upright folds formed by direct uplift or by the transmission of forces through highly competent beds, may have their slopes on both sides of the axial plane identical. The axial plane then cuts the fold into two similar halves or flanks. Such folds are called symmetrical folds. Perfect transmission of the forces in compressional folding is not frequent. Practically all of the upright folds with which the petroleum geologist deals have flanks of unequal size and inclination. They are called asymmetrical folds.

Even these are comparatively few in number and much less important in aggregate production than the asymmetrical folds having slightly inclined axial planes. This type of fold presents a serious problem to the petroleum geologist because of the shifting of the area of accumulation in the lower horizons to the one side or the other of the observed surface crest or axial line. They characterize the folds formed adjacent to mountain folds in incompetent strata.

In the major folds that accompany mountain building, the extreme pressure causes the axial plane to assume an overturned position. This places one flank partly above the other. Such folds are not unknown in oil fields but are seldom of economic importance. Where the force of the thrust is sufficiently great, it is possible for the axial plane to become practically horizontal and the flanks to rest upon each other. These are known as recumbent folds. While there are exceptions to the rule, it is generally felt that the pressures which cause the development of these overturned and recumbent forms will in most cases cause the development of fracturing to such an extent as to permit the escape of any oil and gas that are present in the affected strata. An unusual type of fold related to these, the diapir fold, has been developed in salt-containing strata. It is of such importance that its consideration will be left to a later chapter.

The angles of dip in even the highly folded structures of Tertiary and Cretaceous age are seldom comparable with those of the distinctly mountainous folds. Distinctions between concentric and similar folds are important in these. Their effects are less pronounced in the milder folds that yield oil. Concentric folds are those in which the beds are folded around a common center. As each stratum maintains the same thickness at all places, the folds tend to die out both above and below the competent stratum that causes their existence. In similar folds the angles of dip in successive strata are identical.

The maintenance of the angle necessitates variations in the thickness of the individual beds. In large low angle folds adjustments within the beds may be made without difficulty; this would not be true in mountain folds.

The frequent occurrence of structure in which the vertical closure increases with depth suggests concentric folding. However, as the horizontal area embraced within the closure of the productive anticline seldom appears to decrease with depth, true concentric folding cannot be considered as the cause of the folding. On the other hand, the development of true similar folds in strata of varying competency introduces mechanical difficulties. It would appear logical to consider that most folds in oil fields are combinations of the two types.

Practically all folds in oil fields are of the open type; that is, the beds might be bent even more acutely without materially disturbing the parallelism of the strata. The expression, closed fold, is applied to folds in which further bending will cause distortion. By this we mean materially altering the thickness of the individual beds, thinning them in some places and increasing their thickness in others. When the thinning and thickening have already occurred, the fold is said to have been squeezed. In the sense that the shale and clay between more competent beds have been subjected to some thickening and thinning, the folds in oil-yielding areas may be considered as belonging to these types. However, the variation is small in comparison with the horizontal area of the folds involved. For all practical purposes the majority of oilfield folds must be considered as open types.

Simple Symmetrical Anticlines.—The author knows of no absolutely symmetrical upright anticlinal fold that is productive of oil. Numerous folds of minor size and importance approach the symmetrical in form, but relatively few of the world's important producing areas can be considered of this type. The Elk Hills anticline and the Buena Vista anticline, both in the Valley Field of California, approach the form but deviate in essential points. Several of the productive structures in the Rocky Mountain Province have the general outline of such folds, but their structures and the accumulation of their oil are complicated by faulting. In the Mid-Continent area variations in the porosity of sands prevent even distribution of oil and gas through structures having symmetrical outlines. Several of the producing structures in the Los Angeles Basin of California approach the type closely. Only one, however, can be considered as sufficiently representative of the type to warrant detailed consideration. This is the Sante Fe Springs structure.

Sante Fe Springs, California.[1]—The Sante Fe Springs pool includes a producing area of only about 1,500 acres, but the great thickness of the producing horizons and the high degree of saturation have made it one of the major pools of the world. The discovery well was completed at a depth of 4,595 feet in 1919. Up to the close of 1926 the pool had produced more than 150,000,000 barrels of oil. The structure lies about four miles southeast of the Whittier fault, the major structural feature in that part of the Los Angeles Basin. Its ex-

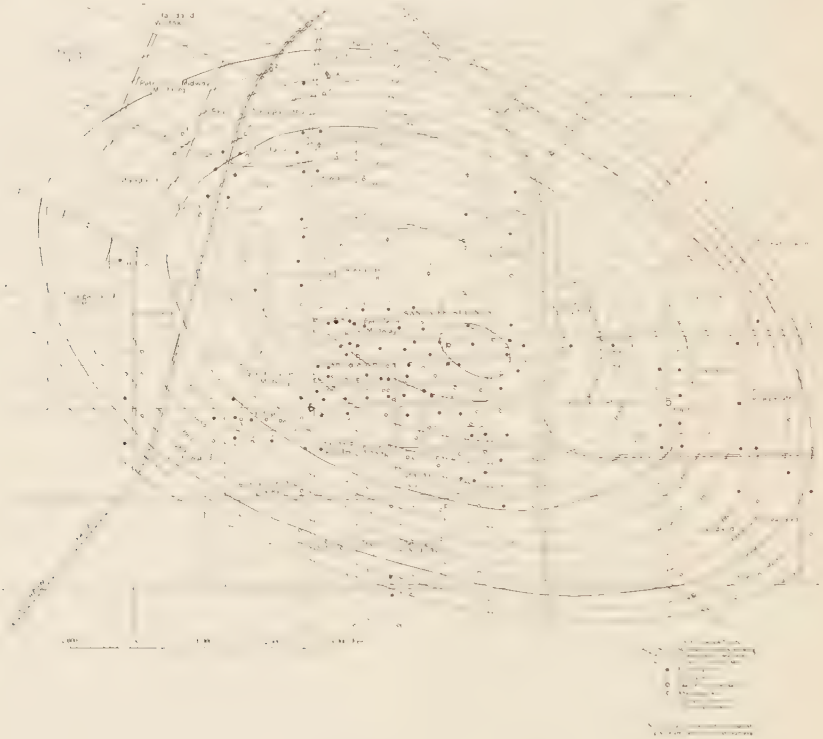


FIG. 50.—Structure map of the Sante Fe Springs pool, California. After English, W. A.: U. S. G. S. Bull. 768, plate 10, 1926.

---

[1] Data on Sante Fe Springs mainly from the following:

Case, J. B.: Report on the Sante Fe Springs Oil Field, California Oil Fields, Vol. 8, No. 11, 1923.

English, Walter A.: Geology and Oil Resources of the Punte Hills Region, Southern California, U. S. G. S. Bull. 768, 1926.

Templeton, R. R., and McCollom, C. R.: Sante Fe Springs Field, California, A. A. P. G. Bull., Vol. 8, pp. 178–194, 1924.

istence is probably due to torsional forces resulting from movements in the underlying crystalline masses along a major fault line. Like many of the pools in the Los Angeles area, the structure was not outlined by examination of outcropping beds. The only indications of possible oil accumulation were a slight elevation of the area topographically and the presence of gas in some water wells. Yet the productive area of the deep Meyer oil zone proves the existence of a definite closure of at least 600 feet.

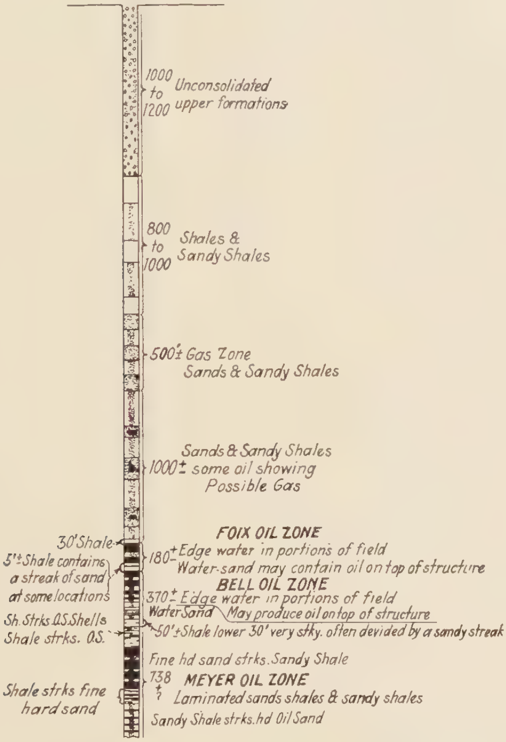

1000 to 1200 Unconsolidated upper formations
800 to 1000 Shales & Sandy Shales
500± Gas Zone
Sands & Sandy Shales
Sands & Sandy Shales
1000± some oil showing
Possible Gas
FOIX OIL ZONE
30'Shale
5'± Shale contains a streak of sand at some locations
180± Edge water in portions of field
Water-sand may contain oil on top of structure
BELL OIL ZONE
370± Edge water in portions of field
Water Sand
May produce oil on top of structure
Sh. Strks O.S. Shells
Shale strks. O.S.
50'± Shale lower 30' very stky. often devided by a sandy streak
Fine hd sand strks. Sandy Shale
738 ±? MEYER OIL ZONE
Laminated sands shales & sandy shales
Shale strks fine hard sand
Sandy Shale strks. hd Oil Sand

Fig. 51.—Ideal graphic log showing geologic formations in the Sante Fe Springs pool. After Case, J. B.: California Oil Fields, Vol. 8, No. 11, Plate 1, May, 1923.

Above the oil horizons lies a shallow gas zone. This is encountered at a depth of 2,000 to 2,100 feet. It appears to be about 1,500 feet in thickness and to consist of sandy shales, sands, and shales with streaks of sand. The gas caused several disastrous blow-outs to drilling wells. At a depth of 3,500 feet, or immediately below the gas zone, is the first or Foix oil zone. It consists of sediments of much the same nature as those above it but is probably more consolidated. The zone has an average thickness of 180 to 185 feet. Wells drilled into it averaged about 1,500 barrels daily in initial production. The horizon is a minor one compared with the underlying zones, its productive area being only about 28 acres. Outside of this area the zone is water-bearing.

At the base of the Foix zone is a thin body of brown shale which separates it from the underlying Bell zone and acts as a cap for the latter. The top of the Bell zone ranges in depth from 3,650 to 3,850 feet in the productive areas. It has an average thickness of 370 feet. The upper 200 feet are oil-bearing in the center of the structure. Below this water is present. The productive area is about 600 acres. The wells had about the same average initial production as those in the Foix zone, but the larger oil-containing area made the aggregate production far more important.

By far the most important of the zones is the deep or Meyer zone. This lies immediately under a sticky brown shale, which forms the base of the Bell zone. The zone itself appears to be about 900 feet thick but is divided by shales into three sub-zones. The wells drilled to the upper subdivision, which is about 100 feet thick, had average initial yields of 4,000 barrels daily; those to the middle zone, 400 feet thick, about 4,500 barrels; and those to the deep zone, 375 feet, an average of 6,000 barrels in the central part of the structure. No water was found between the subdivisions, but edge water was found surrounding the productive areas of each one of them. The productive portions in the upper divisions amounted to about 1,500 acres. The total in the lowest subdivision was considerably less, edge water reaching much closer to the center of the structure than it did in the others.

In each producing zone there is an abrupt change from oil to water on the edges of the producing areas. The level of the edge water is about the same around the oil in each zone. This is a very definite indication of the regular character of the structure and of the even and high porosity of the different zones. Analyses of waters from the different zones indicate that the waters in the Foix and Bell zones are mixtures of altered connate and meteoric waters. Those of the Meyer zone, while altered, are primarily of connate origin. Oil from the Meyer zone averages 34.7° Baume; that of the Bell zone, 30.2° Baume; and that of the Foix, only 26.5° Baume. The differences are probably due to differences in the degree to which they have been affected by the waters with which they have come in contact.

Upright Asymmetrical Anticlines.—Productive structures of the upright asymmetrical type are more common. They occur in practically every oil field of the world. In many of them faulting or variations in the porosity of the productive horizons serve to prevent the concentration of the oil and gas in those points which are most favored by major structural considerations. The effects of changes in porosity are especially noticeable in the producing structures of Paleozoic age. Faulting introduces complications in many of the Tertiary and Cretaceous types.

Two of the structures developed near the Inglewood or Newport-Beverly Hills Fault Zone in the Los Angeles Basin, the Long Beach and the Dominguez anticlines, are excellent examples of this type of structure. They are both free of faults of any size and the unconsolidated nature of their sediments guarantees gravitational separation.

Long Beach, California.[1]—The existence of the Long Beach structure was indicated both by the presence of two dome-like hills, Signal Hill and Reservoir Hill, and by surface dips in the outcrops of the San Pedro formation. Lack of knowledge of the underlying formations and the drilling of deep dry holes in adjacent areas tended to retard interest in the area prior to the discovery of the deep production in the Huntington Beach area lying immediately to the south in 1920. The discovery well was completed in 1921, and the pool had produced up to the close of 1926 more than 200,000,000 barrels of oil. The development of the structure was characterized by much town-lot drilling with its accompanying wasteful expenditure of gas. However, acre yields have been extremely high, and much oil still remains to be recovered.

The shallowest producing zone was the Wilbur, reached at a depth of 2,100 feet at the apex of the structure. It is approximately 200 feet thick but is of little importance as an oil producer. It is water-bearing near the edges of the structure, and the high gas pressure makes control of production difficult in the center. The first important oil horizon is the Alamitos with a thickness of 670 feet. It

---

[1] Data on Long Beach mainly from the following:

Case, J. B., and Keyes, R. L.: Report on the Long Beach Field, California Oil Fields, Vol. 9, No. 4, 1923.

Schwennsen, A. T., Overbeck, R. M., and Dubenduorf, H. H.: The Long Beach Oil Field and Its Problems, A. A. P. G., Vol. 8, pp. 403–423, 1924.

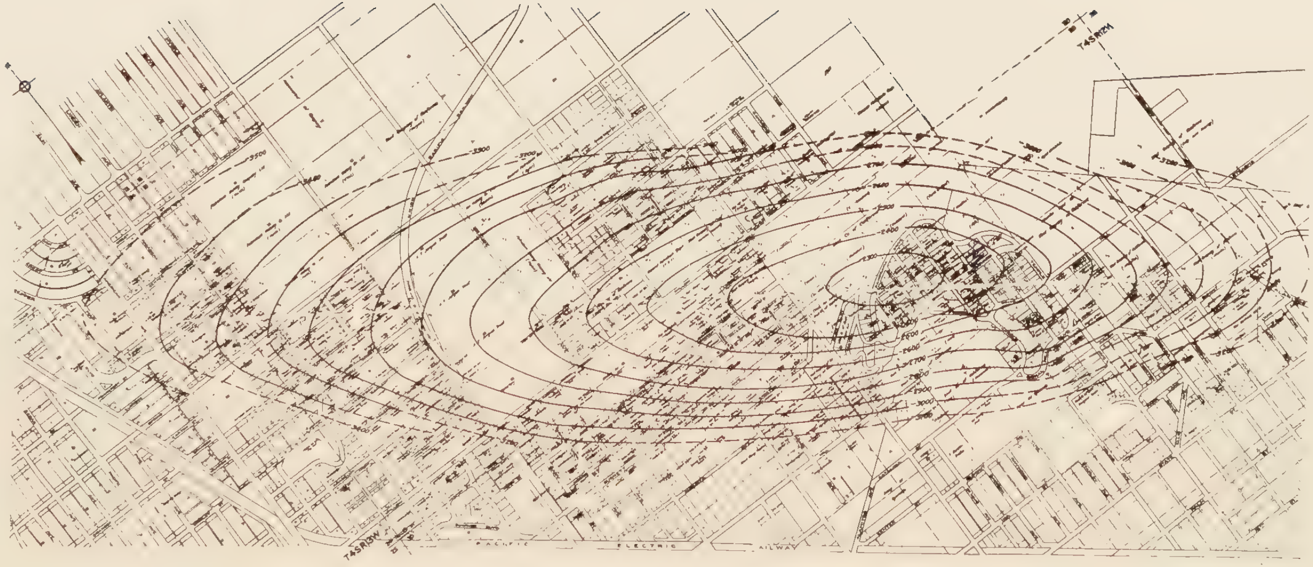


Fig. 52.—Structure map of the Long Beach pool. Contours drawn on the top of the Alamitos zone. After Case, J. B., and Keyes, R. L.: California Oil Fields, Vol. 9, No. 4, Plate 1, Oct., 1923.

really consists of two zones: an upper one with a thickness of 400 feet, and a lower one of 270 feet. The separation rests primarily upon differences in the character of the oil produced rather than upon definite identification of a shale break. The oil in the upper portion is of 21 to 23° Baume while that in the lower averages 25°. Most of the wells drilled to this general horizon produce from both portions at the same time.

Similarly the separation between the lower portion of the zone and the underlying Brown zone is not clearly defined. The Brown zone has a thickness of about 250 feet and yields an oil of 27 to 30° Baume. The Bixby zone, the most important of the horizons of the pool, lies below the Brown. It is separated from it by shales and by a water-containing horizon. It yields oils of 27 to 31° Baume and is con-

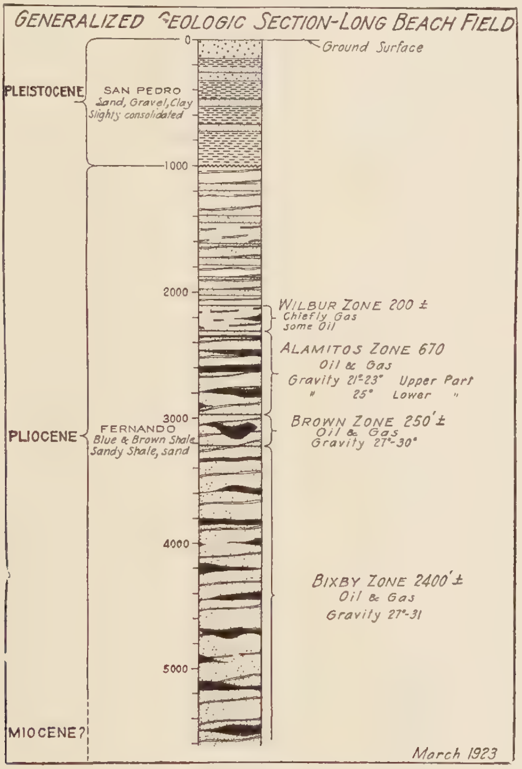


FIG. 53.—Generalized Geologic Section, Long Beach pool. After Schwennesen, A. T., Overbeck, R. M., and Dubendorf, H. H.: A. A. P. G. Bull., Vol. 8, p. 406, 1924.

sidered to be productive through a vertical range of 2,400 feet. A still deeper zone discovered in 1927 extended production to below 6,000 feet.

It must be recognized that these zones are not composed of continuously productive oil sands but are separated by a number of shale breaks into a series of closely related subdivisions. These breaks have probably been of major importance in the accumulation of the oil and in separating it from the waters contained in the horizon. Edge water lines are determined in no small measure by the amount of oil imprisoned in one of these subdivisions. The invasions of edge water as oil is removed may be expected to come differently in different parts of the zone.

The productive horizons are considered as belonging mainly to the Fernando formation of the Pliocene but may extend down to the underlying Miocene. The structure owes its value to intensity of the folding and to the great thickness of the productive zones rather than to large horizontal extent. The proved area is only about 1,200 acres; but the vertical closure is 1,200 feet; and the thickness of the oil-yielding zone, nearly three times that figure. The axis of the productive part of the fold extends in a north-west to south-east direction for a distance of three miles. The greatest productive width is about three-fourths of a mile. The dip of the beds on the southwest flank is considerably greater than that of those on the northeast side. The northwestern end of the fold is somewhat larger than the southeastern.

Dominguez, California.[1] —The discovery well at Dominguez was completed in September, 1923, and the pool passed the 25,000,000-barrel mark in total production in the three years following. The structure is controlled by a few large companies and is being drilled conservatively. Except in the upper zone, its possibilities were still largely unknown three and one-half years after the discovery. The apex of the Dominguez structure lies approximately three miles northwest of that of Long Beach. Structurally it is very similar to the latter, having steeper dips on its southwest flank than on the northeast and a more gentle slope at its northwestern end than at the southeastern extremity.

---

[1] Data on Dominguez mainly from the following:

Dodd, Harold V.: Dominguez Oil Field, California Oil Fields, Vol. 12, No. 4, 1926.

Eaton, J. E.: Geology of the Dominguez Oil Field, O. & G. J., Vol. 25, No. 13, p. 32, Aug. 19, 1926.

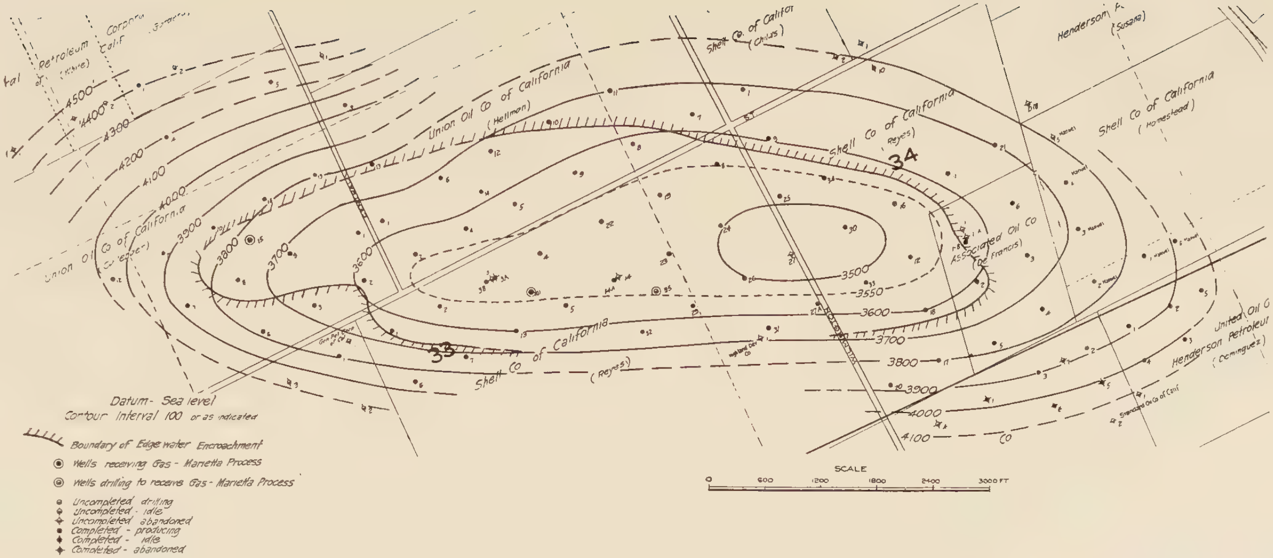

Shell Co. of Califor (Childs)
Henderson P. (Susana)
Shell Co of California (Homestead)
Union Oil Co of California (Hellman)
Shell Co of California (Reyes)
34
33
Associated Oil Co (De Francis)
Shell Co of California (Reyes)
United Oil Co
Henderson Petroleum (Dominguez)
Standard Oil Co of Calif
Union Oil Co of California (Callender)
Petroleum Corp of Calif
4500
4400
4300
4200
4100
4000
3900
3800
3700
3600
3550
3500
Datum - Sea level
Contour Interval 100 or as indicated
Boundary of Edge water Encroachment
Wells receiving Gas - Marietta Process
Wells drilling to receive Gas - Marietta Process
Uncompleted drilling
Uncompleted - idle
Uncompleted abandoned
Completed - producing
Completed - idle
Completed - abandoned
SCALE
0
600
1200
1800
2400
3000 FT

FIG. 54.—Structure map of the Dominguez pool. Contours on the top of the Callender oil zone. After Dodd, H. V.: California Oil Fields, Vol. 12, No. 4, p. 10, Oct., 1926.

The bulk of the production up to the present has come from the Callender zone found at a depth of 3,670 feet at the center of the structure. The zone is considered as approximately equivalent to the Brown zone in Long Beach. Strata equivalent to the Wilbur and Alamitos zones at Long Beach are barren, except for about 100 feet of sand streaked with shale immediately above the Callender zone. This contains small amounts of gas and oil and has been utilized in a few wells. The upper portion of the Callender zone is fairly definite, but the lower portion changes gradually into beds in which shale predominates. The best production probably comes from the upper 200 to 250 feet. Except in edge wells, where the Callender zone contains water, an agreement between the operators has prevented producing from a distance greater than 400 feet below the bottom of the water shut-off. This was usually made immediately above the best portion of the Callender and placed the bottom of the holes in the shale beds. A few edge wells have discovered commercial production below the shale. Several have indicated the probability of commercial production through a considerable vertical range in points located near the center of the structure. No centrally located wells had tested this area up to the time of writing.

The proved area of the Dominguez pool is placed at about 900 acres. This may be increased somewhat by deeper drilling, but the size of lower producing zones is expected to be very little greater than that of the Callender. The closure of the structure is considerably smaller than that at Long Beach and its ability to cause accumulation and retention considerably less.

Inclined Asymmetrical Anticlines.—In the strictest sense the majority of the world's anticlines would probably be called inclined folds. The inclination of the axial plane in most is so slight that it is of minor importance to the geologist in locating test wells. Minor shifts in the position of the axes of the different horizons are not of importance where the structure is largely filled with oil and gas. However, in many of the Rocky Mountain structures the amount of these substances is only sufficient to fill a very small portion of their domed sections. Shifting of the axes in underlying beds may cause the drill to pass through a structurally unfavorable location despite the fact that it was located at the crest of the surface beds. A failure is not only costly but may condemn a structure that is later found to be of considerable value. The difficulties of determining the rate of shift, and in some cases even the direction of shift, are great; and erroneous deductions are not infrequently drawn from the appearance of outcropping beds.

In general it would appear that the majority of inclined folds occur in sections in which the beds have been subject to direct horizontal thrusts rather than in sections where they are the result of vertical uplifts developed from horizontal movements in deeply buried strata. The axial plane tends to slope in the direction of the wider and more gently sloping flank and away from the steeply pitching one. In the case of the Wheeler Ridge structure in the southern part of the Valley Field in California, the axial plane slopes toward the direction of the thrust. In many of the anticlines in the Rockies, it would appear that the axial plane slopes away from the direction of thrust. No entirely satisfactory explanation of the difference is known to the author. Each case must be considered as an individual one in which there has been an individual combination of forces and sediment and basement rock characteristics.

Yenangyat-Singu Anticline, Burma.[1]—The Yenangyat-Singu or Singu pool of Burma is a typical long inclined asymmetrical fold. The productive area is of small size making the location of the crest in the oil horizons important. The wells that were drilled upon the crest as outlined on the surface encountered an extremely thick body of sand but did not produce oil or gas in commercial quantities. The richest and shallowest wells were found along a line parallel to the surface crest but between 300 and 400 feet to the west of it. Careful examination and correlation of the drilling records showed that the great thickness of sand measured on the east side of the fold was due to the nearly vertical position assumed by those sediments. The axial

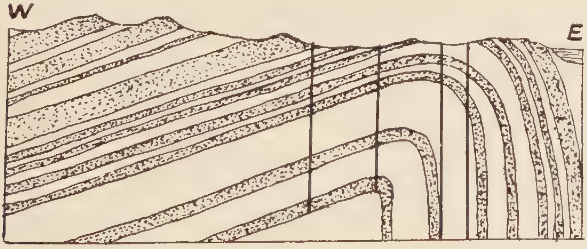


Fig. 55.—Diagrammatic section to illustrate the probable structure of the Yenangyat-Singu anticline. After Thompson, A. B.: Inst. of Min. and Met. Trans., Vol. 20, p. 222, 1911.

---

[1] Pascoe, E. H.: Records, Geol. Survey, India, Vol. 34, pp. 253–260, 1906; and Memoirs, Geol. Survey, India, Vol. 40, pp. 101–123, 1912.

plane was found to make an angle of 36 degrees with the vertical, swinging the axes of each bed farther to the west as the drill went deeper. On the more gently sloping western flank, the decrease in productivity and the encroachment of edge water followed normal lines.

Wheeler Ridge, California.[1]—The Wheeler Ridge structure is responsible for a marked topographic feature—the Wheeler Ridge.

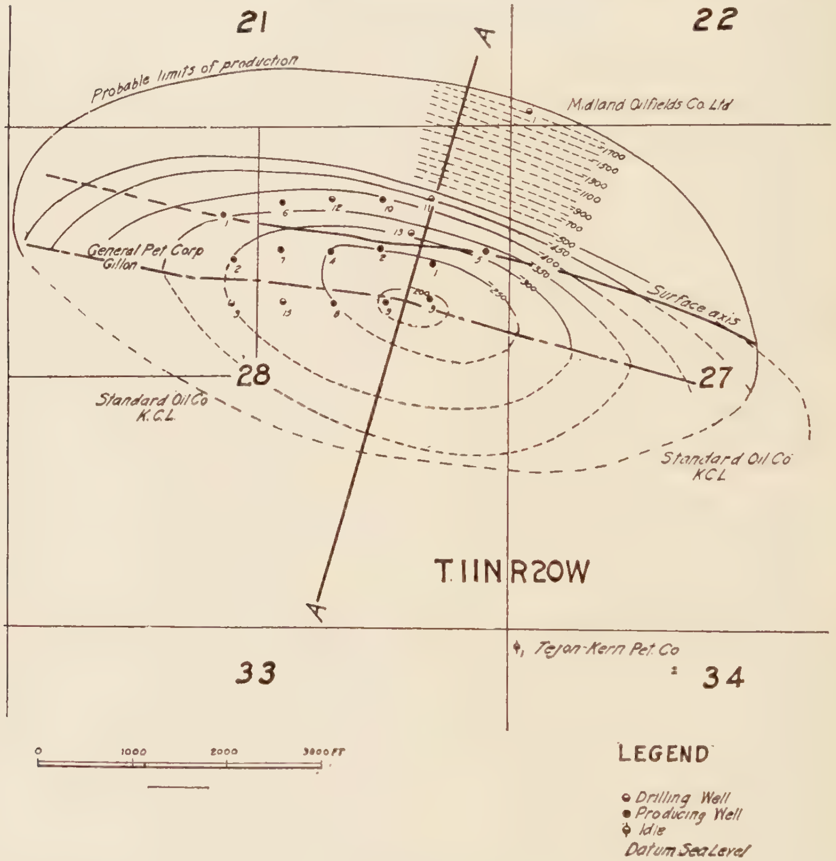


FIG. 56.—Wheeler Ridge Dome. Contours drawn on the top of the second sand zone. After Kaiser, C. L.: California Oil Fields, Vol. 9, No. 12, p. 29, June, 1924.

---

[1] Data on Wheeler Ridge mainly from:

Cunningham, G. M.: The Wheeler Ridge Oil Field, A. A. P. G. Bull. 10, pp. 495–501, 1926.

Kaiser, C. L.: Wheeler Ridge Field, California Oil Fields, Vol. 9, No. 12, pp. 25–29, 1924.

This rises to an elevation of 1,500 feet above the floor of the southern portion of the San Joaquin Valley in California. The structure was tested as early as 1914 by drilling, but the first commercial well was not completed until 1922. Since then a substantial yield has been obtained. The producing portion is a domal area upon a very narrow anticline having a distinct east-west trend. The western end of the major fold ends in a series of faults; the eastern end plunges off. South of the ridge the structure is very complicated, the area being part of the mountain system which ends the valley.

The oil is found in three zones: a tar zone, of no commercial importance found between 1,500 and 1,700 feet of the surface near the axis; a second zone, containing pumping wells which average 150 barrels a day; and the deep zone, in which larger and flowing wells have been developed. There is no true break between the two lower zones which extend from a depth of about 2,100 feet to more than 4,000 feet. The oil in the deep zone is of higher gravity than that of the second, 31° Baume as against 25°, and is under substantial gas pressure.

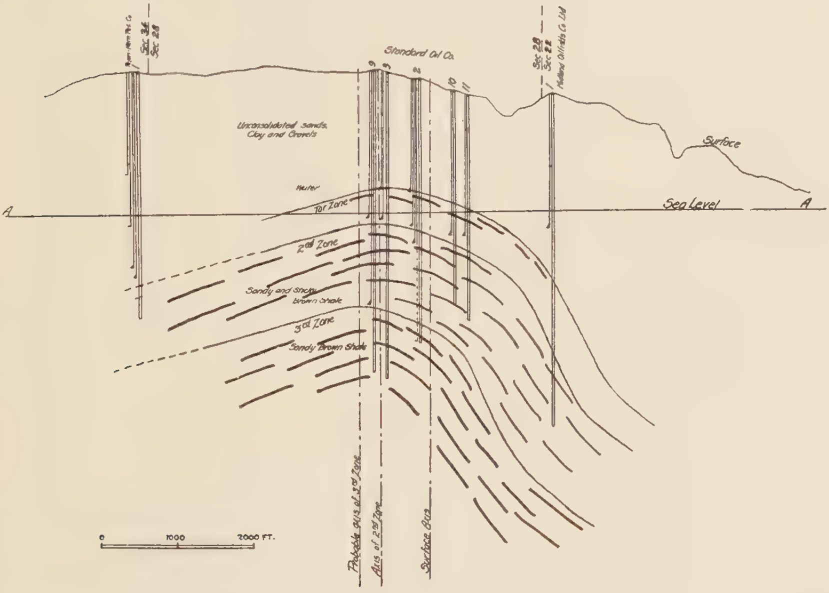


FIG. 57.—Cross-Section of Wheeler Ridge Dome. After Kaiser, C. L.: California Oil Fields, Vol. 9, No. 12, p. 27, June, 1924.

The productive area does not appear to be affected by faulting although major faults occur nearby. The sands are thick and generally considered as regular. The surface beds on the north flank show a dip of between 40 and 50 degrees; those on the south, approximately 10 degrees. The north dip indicated in the underlying beds appears to be even more pronounced. The subsurface axis of the second oil zone is 600 feet to the south of the axis of the surface beds. The axis of the third zone is still farther to the south. The best locations are naturally considerably to the south of the surface crest and the probable productive area different in extent than that which would be outlined by closures on the surface horizons. The structure is controlled almost entirely by one company, and its development has been slow because of low oil prices and the lack of necessity for offset drilling.

Anticlines with Curved Axes.—In the examples cited, the axial planes have been considered as true planes. Vertical curvature of the axial planes probably occurs in some of the folds in the highly contorted strata of the Roumanian and Polish fields. The lack of complete data prevents citing of actual examples of such conditions. Their existence is to be anticipated in sections in which competent and incompetent beds alternate. Horizontal curvature of the axes and of axial planes is of common occurrence. The examples given previously may almost be considered as abnormal in that they have practically straight axes. The majority show simple curvature to some extent. Some go farther and indicate a division of the axis of the fold into two or even more axes. One of these usually remains of major importance, but in some the two divisions of the axis seem to be equal in structural value. Where the sub-axes are roughly parallel, the division may be considered as resulting from variations in the character of the sediments at the time of folding. Where one of the sub-axes makes a large angle with the main axis, the existence of forces working in different directions from those causing the main folding is indicated. In such cases the structure must be considered as being closely related to domal folds in which two axes are fully developed.

Grass Creek, Wyoming.[1]—The anticline upon which the Grass

---

[1] Data on Grass Creek mainly from:

Hewett, D. F., and Lupton, C. T.: Anticlines in the southern part of the Big Horn Basin, Wyoming, U. S. G. S., Bull. 656, 1917.

Estabrook, E. L.: Production problems in the Grass Creek oil field, Mining and Metallurgy, No. 182, pp. 65–66, 1922.

Hewett, D. F.: Geology and Oil and Coal Resources of the Oregon Basin, Meeteetse, and Grass Creek Basin Quadrangles, Wyoming, U. S. G. S., Prof. Paper 145, 1926.

Creek pool is located is found in the southwestern portion of the Big Horn Basin of Wyoming. It is one of a series of folds generally paralleling the main ridges of the Absaroka and related mountain ranges, which lie to the south and west and form the borders of the basin. The anticline coincides roughly in location with a conspicuous basin surrounded by a rugged escarpment of Mesaverde sandstone of the Upper Cretaceous. The discovery well was drilled on the top of

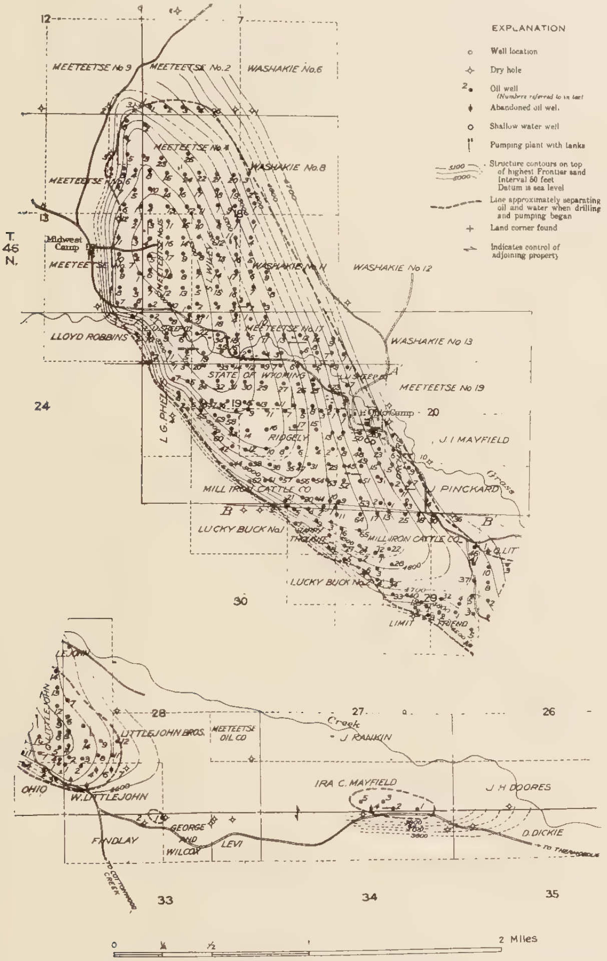


Fig. 58.—Structure map of the Grass Creek oil pool, Hot Springs County, Wyoming. After Hewett, D. F.: U. S. G. S. Prof. Paper 145, Plate XXII, 1926.

TABLE 49.—GEOLOGIC FORMATIONS OF THE BIG HORN BASIN, WYOMING.*

System.	East and west sides of basin.			
	Formation.		Thickness in feet.	Character of rocks.
Quaternary.	Alluvium		0–50	Valley and flood-plain deposits along streams.
	Hot-spring deposits		......	Local deposits of calcareous tufa.
	Terrace gravels		0–30	Gravels and boulders washed from adjacent mountains.
Tertiary.	Volcanic rock.		(?)	Andesitic tuffs and flows on west side of basin.
	Wasatch.		1,300+	Red and drab clay; buff and white sandstone with gravel lenses. Many areas of badlands around border of basin.
	Unconformity			
	Fort Union.		2,000–5,600	Buff and white gritty sandstone, with drab, red, and green clay; lenses of gravel and lenticular beds of coal.
	Unconformity			
Tertiary?	Lance.		840–1,800	Buff and drab sandstone with drab and green shale. No red shale or coal beds.
Cretaceous.	Montana.	Meeteetse.	250–1,400	Soft gray and brown shale; gray and buff sandstone and lenticular beds of coal.
		Mesaverde.	1,120–1,410	Buff and white sandstone, gray and brown shale and lenticular beds of coal near base.
		Cody.	1,900–3,400	Gray, green, and black shale, with calcareous concretions near base, merging with buff sandstone at top. No persistent sharply marked beds.
	Colorado.	Frontier.	494–648	West side: Seven or more beds of gray and buff sandstone with gray and brown shale and bentonite. East side: Two to six or more beds of sandstone.
		Mowry.	160–375	Hard gray shale containing fish scales with lenses of gravel-bearing sandstone.
		Thermopolis.	400–800	Gray to black shale with one persistent sandstone, the Muddy sand of the drillers.
	Cloverly.		110–300	Two beds of massive buff sandstone separated by gray or variegated shale. Upper sand is the Greybull.
Cretaceous?	Morrison.		150–580	Purplish and pale greenish-gray shales with sandstones interbedded.
Jurassic.	Sundance.		250–530	Greenish-gray sandstones and shales with a little limestone interbedded.
Triassic.	Chugwater.		700–1,100	"Red Beds": Red sandstones and shales with a thick bed of gypsum near top.
Carboniferous.	Embar.		250–480	Gray limestone, with gray and red sandy shale and gypsum interbedded. Limestone very thin on east side of basin.
	Tensleep.		30–230	Massive gray sandstone, containing thin layers of limestone.
	Amsden.		150–200	Red sandy shales and sandstones, with layers of limestone and chert.
	Madison.		600–1,000	Gray massive limestones.
Ordovician.	Bighorn.		150–300	Siliceous gray limestone, very hard and massive.
Cambrian.	Deadwood.		700–900	Sandstone, shale, conglomerate, and limestone.

* After Hewett, D. F., and Lupton, C. T.: U. S. G. S. Bull. 656, p. 16, 1917.

the structure as outlined by outcrops in 1914. The development of the pool was largely completed by 1919. The productive area was about 1,600 acres; and the maximum annual production, obtained in 1917, 2,951,000 barrels.

While some oil has been taken from the underlying Morrison, Embar, and Tensleep formations, the bulk of the oil in Grass Creek has come from a series of thin and in part somewhat lenticular sands in the middle of the Frontier formation. The sands occur at widely divergent depths in different parts of the structure because of the intensity of the folding. All wells are, however, comparatively shallow. Excluding the Little Grass Creek dome, which lies immediately west of it, the closure on the Grass Creek structure proper is indicated as being approximately 1,800 feet by surface data. The fold outlined has an extremely steep slope to the southwest and a moderate dip to the northeast. The axis is indicated as having the form of a great arc, its northern end having a north-south strike and its southern end an east-west direction.

The contours drawn in the upper of the productive sands in the Frontier formation correspond very closely in outline with those of the surface beds. The presence of three minor high spots in addition to the major one is indicated. One of these is included within the area of accumulation dominated by the major closure; the others are of very little commercial importance. The axial plane has apparently shifted a little to the northeast, but the shift is so slight that it is of very little importance commercially.

In comparison with other pools in the Rocky Mountains, the productive area of the structure is large. However, oil does not by any means fill the area included within the maximum closure. In addition the edge water line, even at the beginning of operations, was not horizontal but varied in elevation in different parts of the pool. In the southeastern portion of the main producing area, oil extended down to a line 950 feet lower vertically than the elevation of the producing horizon at the apex of the fold. At the northern end water was encountered at a point less than 300 feet lower structurally than the apex. This may be due to lenticularity in sands, which have been assumed to be continuous, or more probably to the effects of circulating waters present in the Frontier sands.

Domes or Quaquaversal Anticlines.—Unless the intensity of the folding along the subaxes developed from the main axis is comparable with the folding along that line, it has little effect upon the general form of the structure. The existence of such action can be inferred where one end of an anticline, or merely the end of one flank, assumes an abnormal width. An excellent example of division of the major axis is found in the Rock Springs uplift. The major axis of that fold divides at both ends. In some of the smaller structures, it would appear that no true axis is present and that the fold is circular or domal.

Some structures, particularly those found in sections containing less consolidated rocks, are so nearly perfect in outline, that contour maps of them appear as a series of concentric lines. In the more consolidated rocks, such as those of the Paleozoic, the perfect domal outline

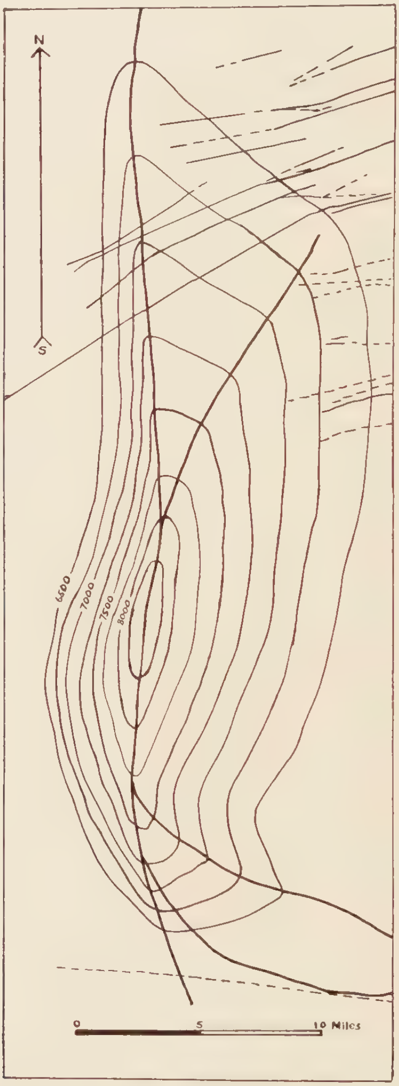


Fig. 59.—Sketch map showing divisions of the axis of the Rock Springs anticline, Wyoming. After Shultz, A. R.: U. S. G. S. Bull. 702, Plate 1, 1920.

is seldom developed except in the smaller structures. Minor irregularities in contour lines, especially those which are based upon accurate subsurface data, tend to modify but not usually to destroy the circular outline. In some of these it is possible to distinguish two axes. One is generally more important than the other, but the angle between them is such as to make it impossible to consider the one as having developed from the other.

Where it is possible to distinguish one axis from the other, it is difficult to consider the structure as having been produced by forces acting in one direction only. In most cases it would appear most logical to consider the structure as the product of two periods of folding in which the forces were applied from different directions. Possibly in the case of minor folds the two axes may be considered as having resulted from unequal compacting above an irregular depositional surface in which similar ridges existed. This can hardly be used in explaining the existence of folds of high closure.

Where the dome shows no definite axes, three explanations other than that of equal compacting may apply. The fold may be considered as the product of two periods of folding, the absence of the two axes being explained by the high plasticity of the unconsolidated sediments. The second possible explanation is that of torsional movement in the underlying basement rocks resulting in straight vertical uplift. The third is that of uplift through the action of rising igneous masses or salt cores. The absence of evidence to support the third explanation forces reliance up the first two in most fields.

Petrolia, Texas.[1]—The Petrolia gas and oil pool has been an important source of oil and gas since 1907. It lies in northern Texas immediately south of a town of the same name. In recent years its gas has been of major interest because of its high content of helium. The productive area is slightly under 15 square miles in extent. From a geologic standpoint the chief interest lies in the outline of the pool. The oil is obtained mainly from the Wichita formation of the Permian age and is reached at a depth of only 300 feet. The gas is found in a series of sands in the Cisco formation of the Pennsylvanian. These lie between 1,550 and 1,700 feet below the surface. About one-third of the wells in this horizon yield oil, but it is known chiefly as a source of gas. The outline of the pool has been completely marked by the drilling of dry holes, which demonstrate that the occurrence of the oil and gas is closely controlled by structural conditions.

---

[1] Data on Petrolia mainly from:

Shaw, E. W.: Gas in the area north and west of Fort Worth, U. S. G. S. Bull. No. 629, pp. 15–75, 1916.

Shaw, E. W., and Ports, P. L.: Natural gas resources available to Dallas and other cities of central north Texas, U. S. G. S. Bull. 716, pp. 55–91, 1921.

The structure is of unusual shape. The strike of the major axis of the fold is slightly west of north. A subordinate but very definitely outlined axis extends to the northeast and gives the area contained within the closure the general outline of a very broad letter "Y." In the northern part of the structure between the two axes, there is a relatively steep rising syncline.

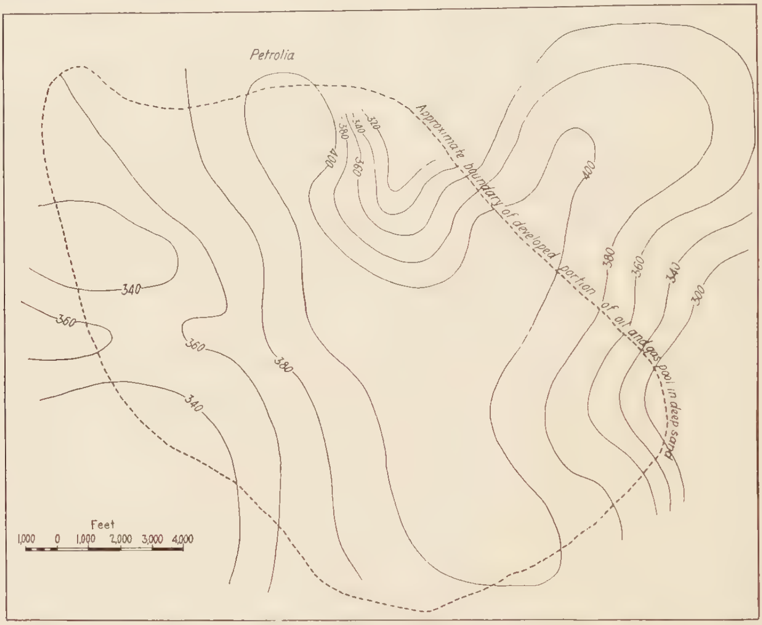


FIG. 60.—Structural map of the Petrolia pool, Texas. Contours on the gas sand. After Shaw, E. W., and Robinson, H. M.: U. S. G. S. Bull. 716, p. 67, 1921.

The explanation of the form of the structure is difficult. The most logical explanation seems to be that of a cross anticline resulting from two systems of folding of unequal intensity, the thrusts being from directions perpendicular to the strikes of the axes.

Bald Hill Dome, Oklahoma.[1]—The Bald Hill Dome lies in the northern portion of Township 20 north Range 12 east in the eastern part of Osage County, Oklahoma. It was one of the first areas to be

[1] Ross, C. S.: U. S. G. S. Bull. 686–N, 1922.

developed in that state, drilling beginning in 1908 and reaching its crest in 1914. The structure was never a sensational one, the average initial production of the wells being only about 40 barrels a day. However, the yields were well maintained, and the conditions were representative of the productive areas in the eastern portion of the Osage country, which contributed so much to production during the early development of Oklahoma.

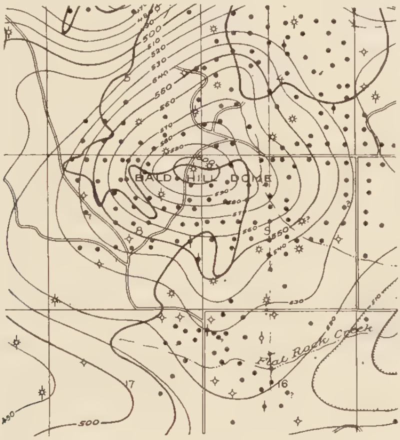


FIG. 61.—Bald Hill Dome, Eastern Osage County, Oklahoma. Contours based on outcropping beds. After Ross, C. S.: U. S. G. S. Bull. 686, Plate XXVII, 1922.

The structure is outlined in surface beds of Pennsylvanian age. The location of the wells shows close agreement between surface structure and subsurface conditions. The greater part of the oil was contained in the Bartlesville sand of the Pennsylvanian, but some wells found substantial amounts in the Mississippi lime. The Bartlesville lies about 1,500 feet below the surface; the Mississippi lime, about 400 feet deeper. The thickness of the Bartlesville varies from 50 to 170 feet, but only parts of this can be considered as sufficiently porous to be commercially productive. Variations in sand porosity were important in determining the yields from adjacent wells, but were not sufficiently marked to affect the general anticlinal distribution of the oil.

The dome is nearly circular in form, but there is a slight indication of a north-south axis. The normal dip of the beds in this area is toward the west. The dip away from the center of the structure in that direction is more pronounced than to the east. To the northeast the beds lie in a terrace-like position and are oil-bearing, but in general production is limited to the area contained within the closure. This amounts to about 70 feet in the surface formations and includes a productive radius from the crest of nearly a mile.

The Bald Hill Dome is one of the larger domal structures that are so common in northeastern Oklahoma. They are found in close association with typical small anticlines, terraces, plunging anticlines, and small faults. The absence of evidence of any strong individual force makes explanation of their presence difficult. The explanation that appears to be most generally accepted at present is that of uplift through torsional action resulting from horizontal movements in the underlying rocks.

Hogback Dome, New Mexico.[1]—The Hogback pool was the first of a group of pools to be opened up in the northwestern portion of the state of New Mexico. The discovery well was completed in 1922 and produced at the rate of 350 barrels daily, yielding oil of 61° Baume gravity. Perhaps the most important thing about this pool and the others adjacent to it is the unusually high character of the oil.

The Hogback and associated structures are sharply defined domal structures in a region of otherwise moderate dips. The Hogback structure itself has a closure which, according to surface observations, would include approximately 18,000 acres. The producing portion of the structures is less than half of one square mile in extent. The surface structure shows the area within the closure to be triangular rather than circular. The dip on the east and southeast portions is somewhat steeper than the slope to the north and west. The outline of the area immediately adjacent to the apex of the fold, as indicated by subsurface contours drawn from well data, shows the existence of north-south axis of greater size than the east-west and tends to give the fold an anticlinal appearance.

The producing horizon is a thin sandstone in the Dakota formation. This is possibly somewhat lenticular, but the variations in its porosity have not affected the accumulation of oil to any great extent. The producing wells reached the sand at depths of less than 800 feet. The subsurface contour map shows a difference of less than 20 feet between the top of the Dakota sandstone in the well that was located highest on the structure and those which contained edge water. The wells flowed naturally. This was not due to gas pressure but to the heavy water pressure, the Dakota being water-bearing wherever penetrated away from the apex of the fold.

---

[1] Nowels, K. B.: Navajo Reservation Development, O. & G. J., Vol. 24, No. 19, pp. 255– , Oct. 1, 1925.

The forms of the Hogback and other structural features of the area are considered as due to local uplifts caused by the Carrizo Mountains to the west, the La Plata Mountains to the northeast, and Ute Mountain to the north. These are mainly of igneous origin. In the San Juan Basin in which the structure lies there is considerable evidence of igneous action in the form of plugs and dikes, but there is no evidence to indicate that the oil-yielding domes are of laccolithic origin.

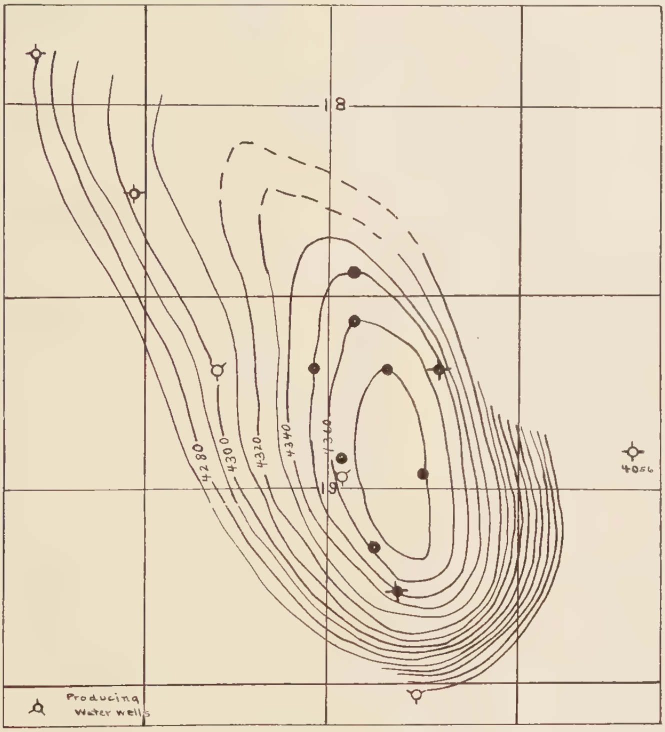


FIG. 62.—Structure map of the Hogback pool, New Mexico. Contours on the top of the Dakota sandstone. After Nowels, K. B.: Oil and Gas Journal, Oct. 1, 1925, p. 256.

Lost Soldier Dome, Wyoming.[1]—The Lost Soldier Dome is one of a series of folds that are found in the Lost Soldier-Ferris district of south central Wyoming. This district lies at the northern end of the Rawlins uplift, one of the major upfolds of the Rocky Mountains in that state. The general outline of the dome is indicated by outcropping Cretaceous strata, but much of the structure is concealed by alluvium. The size of the closure, 3,100 feet, made it possible to work out the structure despite this handicap. The first well was completed in 1916 at a depth of 239 feet. It was located on the apex of the dome. It produced from the Upper Frontier sand in which the oil-containing area was only 160 acres. Other sands of minor importance were encountered in the Frontier formation.

The Mowry formation immediately below was also productive. Wells averaged 200 barrels in initial production, and the oil-containing area amounted to more than a square mile. The most important horizon, however, was the Dakota in which wells having an initial yield of from 300 to 4,000 barrels were completed. Several wells yielded very large flows immediately above the Dakota and were considered to have penetrated fault fissures. The Dakota was of considerably greater lateral extent than the upper formations; and the yield from it, of greater importance. Production was obtained from the Lakota also, and in 1926 a well was completed in the Sundance. By the end of 1926 the total number of producing wells in all horizons had increased to 70, and their combined production for the year was 1,909,000 barrels.

The Lost Soldier Dome is elongated in a N. 30 W. direction. Otherwise it has the form of a true dome. The slopes on the northern and southern ends are not as steep as those on east and west sides. The structure is complicated by faulting, especially to the north and east. Most of the faults are beyond the productive area and of little importance. Some apparently cut the productive portions as well. The faults have not affected the anticlinal accumulation but have evidently permitted circulation between one horizon and another. Improvement in recovery from wells in the Frontier has been noted as resulting when wells in the Dakota were shut down temporarily.

The structural history of the area in which Lost Soldier lies is a somewhat confused one. The major structural movement was probably that during which the Rawlins uplift was formed. The alignment of the oil- and gas-containing folds is transverse to the major axis of that uplift. This suggests the probability that other forces

---

[1] Data on Lost Soldier mainly from:

Fath, A. E., and Moulton, G. F.: Oil and Gas Fields of the Lost Soldier-Ferris District, Wyoming, U. S. G. S. Bull. 756, 1924.

Krampert, E. W.: The Rawlins-Lost Soldier District, A. A. P. G. Bull. 7, pp. 131–146, 1923.

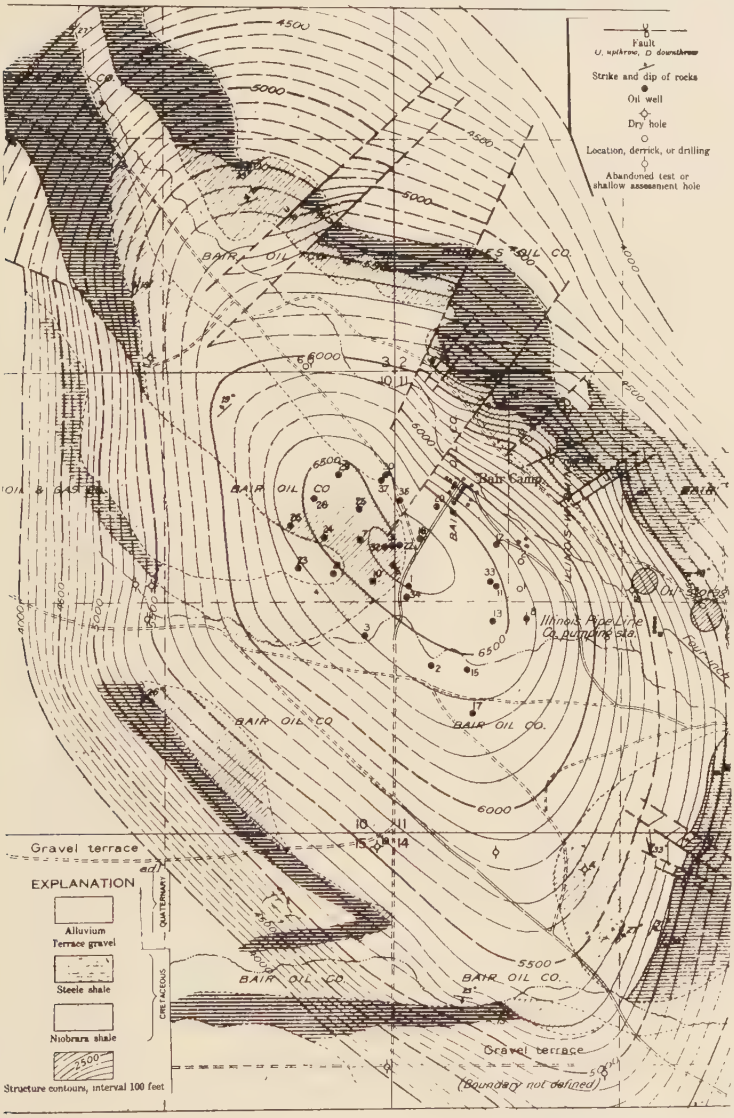


FIG. 63.—The Lost Soldier Dome, Wyoming. Structure on the Wall Creek sand. After Fath, A. E., and Moulton, G. F.: U. S. G. S. Bull. 756, p. 33, 1924.

TABLE 50.—ROCK FORMATIONS OF THE RAWLINS-LOST SOLDIER DISTRICT IN CENTRAL WYOMING.*

System	Series	Group	Formati	Thickness in Feet	Characteristics
Quaternary		Recent		0–300	Sand dunes. Lake beds. Alluvium. Terrace gravels.
	Unconformity				
Tertiary	Eocene		Wasatch	1,800	Freshwater white ss. and sh. Local coal.
		Unconformity			
			Fort Union	6,000	Alternating beds yellowish-brown ss. and drab sh. Beds of rusty brown ss. in lower part. Local coal.
	Unconformity				
?	?		Laramie	1,500	Alternating beds yellowish-brown ss. and dark sh. Local coal.
Cretaceous	Upper Cretaceous	Montana	Lewis	1,000	Dark drab sh. including local ss. and beds of coal.
			Mesaverde	1,500–2,000	Alternating beds ss. and drab sh. with beds of coal. Prominent beds white ss. at top and bottom.
			Steele	4,520	Dark sh. upper part sdy. grading upward into ss. Lower part slightly sdy. with irregular sand at base.
		Colorado	Niobrara	1,385	Dark gray sh. with several persistent concretionary claystone beds at top. Upper 400 ft. might have been included in Steele sh. Lower 300 ft. may be Carlile sh.
			Frontier	660	Upper part consists of from 3 to 7 sandstones with thinner beds of sh. Lower part dark gray sh. with occasional thin ss.
			Mowry	360	Dark fissile sh., weathering silver gray on exposed surfaces.
			Thermopolis	75	Black sh. with sandy layers and one or more thin white sandstones.
Cretaceous	Lower Cretaceous	Cloverly	Dakota	40	Uniform fine-grained white ss.
			Fuson	105	Dark gray sh. above vari-colored sh. below, sometimes sandy.
			Lakota	60	Massive conglomeratic ss.
	Local Unconformity				
Jurassic			Morrison	225	Gray and greenish sh. alternating with green sdy. sh. and white ss.
			Sundance	625	Fossiliferous ls. and gray sh. above. Buff ss. below.
Triassic Permian			Chugwater	1,200	Bright red sh. and ss. several prominent beds of white ls.
Permian			Embar	660	Pink and white ls. alternating with red limy shale. Gypsum.
Pennsylvanian			Tensleep	450	Massive white ss. above. Thinner bedded ss. alternating with sh. below.
Mississippian			Madison	350	Massive white ls.
	Unconformity				
Cambrian			Deadwood	400	Purple to pink quartzite.
	Unconformity				
Archean					Pink granite.

---

* After Kampert, E. W.: A. A. P. G. Bull., Vol. 7, pp. 138–139.

assisted, if they did not dominate, the making of the group of folds in which Lost Soldier is located.

Cotton Valley, Louisiana.[1]—The Cotton Valley oil and gas pool is situated in the northern part of Webster Parish, Louisiana. Surface outcrops were not satisfactory, and its discovery was the result of an intensive wildcat drilling campaign to develop other structures similar to the nearby Homer and Haynesville pools. The discovery well was a large gasser and was completed in August of 1922. In November of the following year, another gas well came in spraying oil. The structure produced both large gas wells, some up to 60,000,000 cubic feet in capacity, and flowing oil wells.

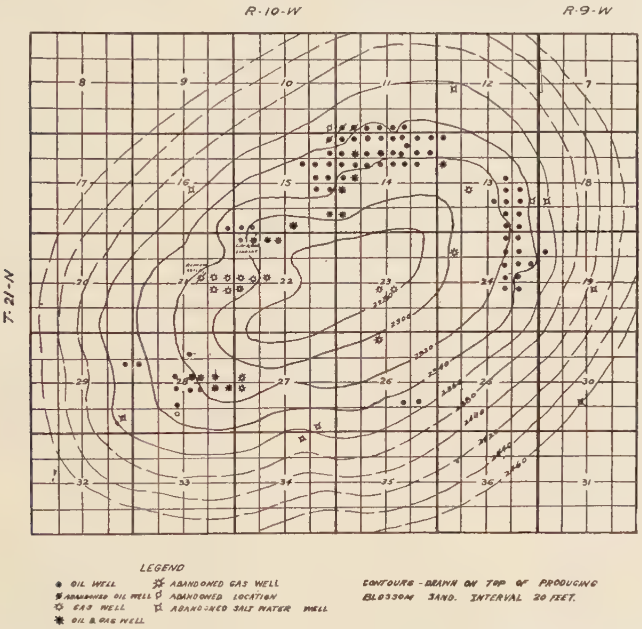


FIG. 64.—Sub Surface map of the Cotton Valley Pool, Webster Parish, Louisiana. After McDonald, Worth W.: A. A. P. G. Bull., Vol. 9, p. 876, 1925.

The structure is one of a number of domal folds found in the northwestern part of Louisiana. As outlined by contours drawn upon the Blossom sand from which the production has been obtained, the structure is shown to have some axial development in a northeast to southwest direction. In addition there is a minor axis extending to the northwest. Wells near the top of the structure were approximately 2,500 feet deep. They reached the producing horizon at a subsea depth of 2,280 feet. The water line was usually found at a subsea depth of 2,340 to 2,345, but in some places water appeared at depths less than that, and in others oil was found at greater depths. In general gas occupied all of the center of the structure, and oil was limited to a comparatively narrow belt between it and the water.

---

[1] McDonald, Worth W.: The Cotton Valley, Louisiana, Oil Field, A. A. P. G., Vol. 9, pp. 875–885, 1925.

TABLE 51.—FORMATIONS IN THE OIL AND GAS FIELD OF NORTHERN LOUISIANA AND SOUTHERN ARKANSAS.*

System, Series, Group, Formation	Principal Characteristics	Maximum Thickness in Feet	Productive Pools
Tertiary, Eocene, Claiborne, (1) Cockfield	Gray sand, some clay, shale, lignite, and quartzitic sandstone, non-marine.	450	
(2) St. Maurice	Limonitic clay, sand, calcareous glauconitic shales, marine.	400	
(3) Wilcox	Sand, clay, shale, lignite, calcareous boulders, glauconitic.	600	
(4) Midway	Clay, limestone, chalk, some lignite, gypsum.	400	
Cretaceous, Gulf (5) Arkadelphia	Dark clay, shale, chalk near bottom, marine.	600	
(6) Nacatoch	Fossiliferous limestone, glauconitic sand.	200	Gas at Caddo, Shreveport, Bethany, El Dorado, and Smackover. Oil at Homer, El Dorado, Bellevue, and Smackover.
(7) Marlbrook	Marl, chalk.	350	
(8) Annona	Chalk.	600	Gas at Monroe (?) Oil at Caddo.
(9) Brownstown	Marl, chalk.	300	
Bingen, (10) Blossom	Calcareous, glauconitic sand.	150	Gas at Bethany and Webster. Oil at Homer, Haynesville, Smackover, and Stephens.
(11) Eagle Ford	Shale, calcareous and red in places. Sandy at bottom.	600	Oil at Caddo and De Soto.
(12) Woodbine	Sandy, lignitiferous.	150 (?) Doubtfully present	Gas at Bethany (?)
Cretaceous, Commanche, (13) Washita group	Limestones and clays.	300 (?)	Gas at Bethany.
(14) Fredericksburg group	Limestone.	50 to 100 (?)	
Trinity group (15) Glen Rose	Limestone.	100 (?)	Oil at Caddo (Pine Island).

* After Hull, J. P. D.: A. A. P. G. Bull., No. 7, p. 364, 1923.

Wells were drilled through Eocene and parts of the Upper Cretaceous prior to reaching the producing horizon, which has been correlated with the horizons in other pools and identified as the Blossom sand. This places it at the top of the Eagle Ford shales. A deep test on the center of the structure found a substantial volume of gas at 4,200 feet. This has been identified as the Upper Glen Rose horizon and suggests the possibility of oil in other parts of the structure in that horizon and the advisability of even deeper drilling.

The Cotton Valley structure is one of considerable size. The area contained in the structural closure is large, that contained in the productive area alone being 6,000 acres. Compared to its horizontal extent the vertical closure is not large. The structure is one of a series of domal folds located upon the Sabine and Camden uplift areas. Important as these pools are, it is not possible at the present time to explain the manner of their origin with any degree of certainty. The study of surface conditions is difficult, and the great thickness of largely incompetent beds obscures the action of the forces that caused the development of the forms now being outlined by the drill.

Terraces and Plunging Anticlines.—The factors that are instrumental in causing the development of strong folds with true closures are also likely to cause the development of incipient folds when applied with less force. In the tilting of large areas of sediments, one does not expect that the rate of dip resulting will be uniform throughout. When true folds are formed, the forces applied may also be expected to produce incipient folds where the combination of conditions is less favorable. Where the amount of the tilting of strata is large, the variations of the monoclinal slope or the minor partial folds associated with the stronger true folds may have little influence upon the movement of oil and gas. The decrease in the dip in a loose Tertiary horizon from 25 down to 20 degrees might delay the rate of movement of the oil and gas up the slope, but it would hardly be expected to have any permanent effect. The geologist pays little attention to such variations in the highly tilted and folded rocks from which the greater portion of the world's Tertiary and Cretaceous production is obtained.

However, where the dips average between 50 and 100 feet to the mile and the sands are tightly compacted and cemented, slight decreases in the rates of dip may terminate movements and initiate accumulation. The termination of the movement implies the presence of conditions which tend to neutralize the forces causing movement of the oil and gas up the slope of the horizon containing them. This means in most cases that the slope of the container horizon is so reduced that the force resulting from the vertical movement, which tends to cause horizontal migration, is not sufficient to overcome frictional and capillary resistance. Movement away from the basinal area, if continued, is due to the push from that direction. In the absence of distinct artesian circulation of the water, the push would be limited in amount. Some force for such action might be generated by decrease in the pore space of container rocks through gravitational or dynamic compacting. It is not certain what portion of the force so generated would be effective in causing movement. Similarly the buoyancy of gas and oil trapped basin-ward from the oil on the terraced flat area would tend to force it across that section.

If the terrace were narrow, the renewal of the movement would follow shortly after its cessation. The actual amount of oil trapped permanently would be small. This condition appears to have occurred in the great majority of the terraced sections. However, where the terraced area is comparatively large and the slope of the rocks basin-ward from it very slight, the forces available for pushing action may not be sufficient to cause such movement across the full width of the terrace. In many cases they do not appear to have been strong enough to move all of the oil from the sloping beds on the basin-ward side of the terrace.

Unless variations in porosity accompany the terracing, the development of high gas pressures is not likely to occur. Because of this such areas are known chiefly as areas of small wells. In general they tend to yield oil rather than to contain gas.

Accumulation in terraced sections is shown best in the true terrace. This may be considered as a practically flat belt having considerable extent along the strike of the beds. The same conditions apply where the terraced section is of "V" shape with the bottom of the "V" pointing basin-ward. In this the area of accumulation is more localized, but the factors causing it are the same. Such areas are known as plunging anticlines or noses. Closely related to the nose, and at the same time resembling the closed anticline are the anticlinal terraces. In these the axis of the incipient fold is nearly parallel to the strike of the rocks in the area. There is some slight reversal of dip but no true closure. The accumulation naturally resembles to some extent that of the closed anticline.

Numerous cases of structures of these types appear in the surface contour maps of producing areas in the Paleozoic fields of the United States. A few pools producing from the Cretaceous appear to belong to this group also. However, the fact that the productive area appears to conform with the area considered most desirable from the theoretical standpoint does not definitely prove the production to be caused by terracing. In many of the terraced types of structures in the Mid-Continent area, the structure of the producing horizon has been found to be a true fold. The terrace or nose in the surface beds is merely a surface manifestation of a true fold, which dies out as it reaches the upper beds and the surface. In other cases, while the terracing continues, changes in porosity of the sands must be considered as of greater importance in causing accumulation.

Eastern Osage, Oklahoma.—The eastern portion of Osage County in Oklahoma contains a number of examples of accumulation in terraced types of structures. In most cases the accumulations are due in part to porosity variations, making it difficult to cite simple examples. Practically all of the areas are of small size. Wells of 10 to 100 barrels initial capacity are general; those of larger yield, exceptional. Some of the production comes from other horizons, but the great bulk of the oil has been taken from the Bartlesville sand and the Mississippi lime.

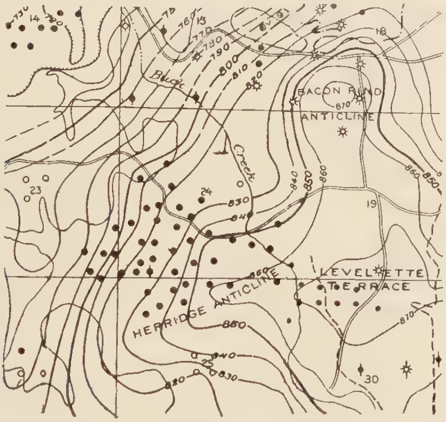


FIG. 65.—Structure map of the Herridge plunging anticline, Levelette terrace and adjacent areas in T. 27 N. R. 10 and 11 E., Osage County, Oklahoma. After Robinson, H. M., and Mills, R. V. A.: U. S. G. S. Bull. 686, Plates XLVI and XLI, 1922.

One case of a producing area belonging to this group is found in the western portion of T. 27 N. R. 11 E. and the eastern portion of

T. 27 N. R. 10 E.[1] The pool developed here obtained production in the Mississippi lime. The terrace on which the oil wells have been drilled is closely allied with an anticlinal area to the east known as the Elkins anticline. The terraced area itself contains a central flat section called the Levelette terrace. To the north this passes into a plunging anticline called the Bacon Rind anticline. This portion might be called a dome as it contains a closure of 10 feet.

To the south a very shallow rising syncline separates it from an anticlinal area called the Sand Creek anticline. To the west the central terrace area changes into a plunging anticline known as the Herridge anticline.

The structure map shown was drawn on surface beds. It is probable that the structure of the Mississippi lime is somewhat more acutely outlined, but the general form is believed to be maintained. Gas is prominent in the area of the Bacon Rind anticline and also to the east on the Elkins anticline. Oil has been taken in substantial amounts from the steep western slope of the Herridge anticline and from the western portion of the flat Levelette terrace. The wells were not large, the initial production being only about 20 barrels daily. Drilling costs were low, however, and production was fairly well sustained. The gas wells to the east and in the Bacon Rind dome were small, yielding only 2,500,000 to 4,000,000 cubic feet daily.

The productive area in the Mississippi lime is not reflected by commercial production of oil in the Bartlesville sand, which lies above it in the Cherokee shales. The sand appears to be too tightly cemented to yield oil commercially in this locality. It is productive some distance to the south and west, however. The outline of the productive area of the Levelette terrace and the Herridge plunging anticline undoubtedly reflects the position of the Elkins anticline to the east of it. The closure of that fold is less than 20 feet and the area hardly sufficient to control accumulation on the Herridge plunging anticline two to three miles to the west of its axis. There accumulation of oil must be considered as due primarily to the absence of sufficient slope to maintain movement.

A similar condition is found in T. 21 N. R. 12 E.[2] immediately to the northwest of the Bald Hill Dome described on page 272. Here the terraced area has the form of a typical anticlinal terrace, its axis having a northeast strike and being parallel to the general strike of the beds in the area. One 10-foot closure has been drawn in the contour map of the surface beds, but its size is insignificant compared with the size of the productive area. A flat slightly synclinal area lies east of the anticlinal terrace, which is known as the Delaware anticline. The synclinal area partly separates the producing area of the Delaware anticline from the Bald Hill Dome and the northern extensions of the latter. Part of the synclinal area is productive. To the east another terraced section occurs. The more favorably located wells show somewhat larger initial yields, those on the crest and west flank of the Delaware anticlinal terrace being larger producers than those to its east. Practically all of the wells are in the Bartlesville horizon. They are similar in behavior to those of the Bald Hill Dome. Operations have been satisfactory as the wells, while yielding only 45 barrels daily in initial production, have been long lived and are of shallow depth.

---

[1] Robinson, H. M., and Mills, R. V. A.: U. S. G. S. Bull. 686, Parts T and V, 1922.

[2] Ross, C. S.: U. S. G. S. Bull. 686, Part N, 1922.

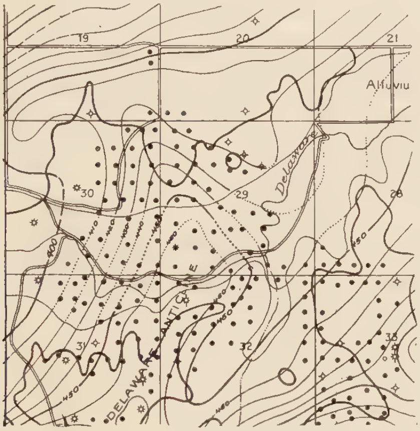


FIG. 66.—Structure map of the Delaware anticlinal terrace, T. 21 N. R. 12 E., Eastern Osage County, Oklahoma. After Ross, C. S.: U. S. G. S. Bull. 686, Plate XXVII, 1922.

Berea Grit Pools, Ohio.[1]—One of the most extensive producing horizons in southeastern Ohio is the Berea grit of the Mississippian. The area is one in which the normal dip is to the southeast toward the axis of the Appalachian geosyncline. The rate of dip averages about 50 feet to the mile. There are very few strong structural features in the area. The productive belts not only in the Berea but also in other horizons are limited largely by porosity variations and slight changes in the rate of dip. It is difficult in many places to determine which of the two factors was the more effective.

---

[1] Condit, D. Dale: Structure of the Berea Oil Sand in the Woodsfield Quadrangle, Belmont, Monroe, Noble, and Guernsey Counties, Ohio, U. S. G. S. Bull. No. 621, pp. 233–249, 1916.

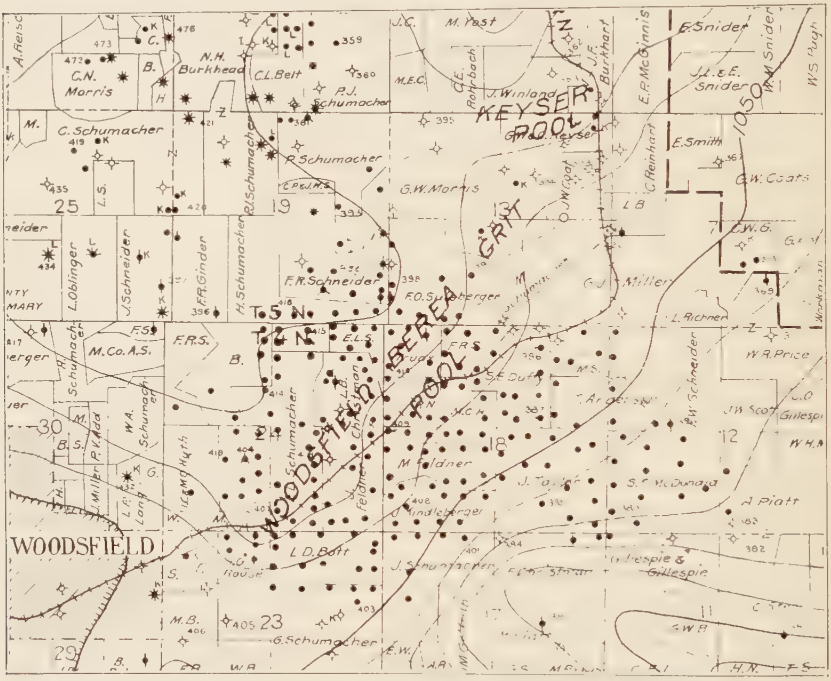


FIG. 67.—Structure of the Berea sand in the Woodsfield pool, southeastern Ohio. After Condit, D. D., and Mills, R. V. A.: U. S. G. S. Bull. 621, Plate XXIV, 1916.

In the Woodsfield pool in which production was obtained from the Berea grit, the accumulation seems to follow very closely the outline of a broad plunging anticline. The flat portion of the structure was largely an area of minor showings of oil with some gas. The gas is most prominent in the northern portion of the area in what is locally known as the Burkhart pool. The bulk of the oil was found along the southeastern or frontal portion of the broad plunging anticline. Its occurrence there reflects its inability to maintain movement to the northwest across the flat terraced section. Migration is naturally difficult because of the fact that the thickness of the sand as a whole is only from 20 to 30 feet and the portions that are porous enough to yield oil and gas in commercial quantities less than that. The so-called "pay sands" or more porous parts are probably lenticular, and the movement from one of them to another is difficult even though there is no true barrier between them.

Osage Pool, Wyoming.[1]—While conditions in the areas of the Osage and in southeastern Ohio, which have just been discussed, are representative of a large number of accumulations in the Mid-Continent and Eastern Provinces, similar conditions in the Osage pool of eastern Wyoming are different from those in other parts of the Rockies.

The Osage pool is located in Weston County, Wyoming. It lies on the western slope of the Black Hills uplift. The strata throughout the area dip at the rate of five degrees toward the southwest. Locally the dip may vary from practically nothing to as much as 20 degrees. No closures have been mapped on the surface beds.

The chief source of oil in the area is the Newcastle sandstone of the Graneros shale. Oil is known to occur in other beds both above and below the Newcastle, but they are of minor importance. The producing area is commonly divided into an area of shallow wells averaging less than 500 feet in depth and a section of deep producers with an average depth of 1,400 feet. The two zones are characterized by low dips and the intervening area by steeply dipping beds. The upper terraced area is the better known because of the larger number of wells that have been drilled upon it. The belt between it and the lower terrace to the southwest has yielded oil, but the size of the wells has not been sufficient to warrant drilling to the depths of 800 to 1,300 feet needed there. The average yield of the wells in the upper terrace and the adjacent steep zone is less than five barrels a day.

The deeper wells on the lower terrace are more costly to drill. However, they are considerably more productive. Some of them contain gas. This is not present in any quantity on the upper terrace.

The Newcastle sandstone outcrops on the eastern margin of the upper terrace. This has probably permitted the greater part of the original gas and some of the oil to escape. That remaining is logically under very slight pressure. As the Newcastle sand varies considerably in thickness and porosity in different sections, the productivity of the wells is not based solely upon structural conditions. Collier[1] states that the deep discovery well was located at a point near the edge of the zone of steeply dipping rocks between the two terraces. Yet it had a strong gas pressure. The explanation of this is difficult as there is no known structural barrier to the migration of

---

[1] Collier, A. J.: The Osage Oil Field, Weston County, Wyoming, U. S. G. S. Bull. No. 736, pp. 71–110, 1923.

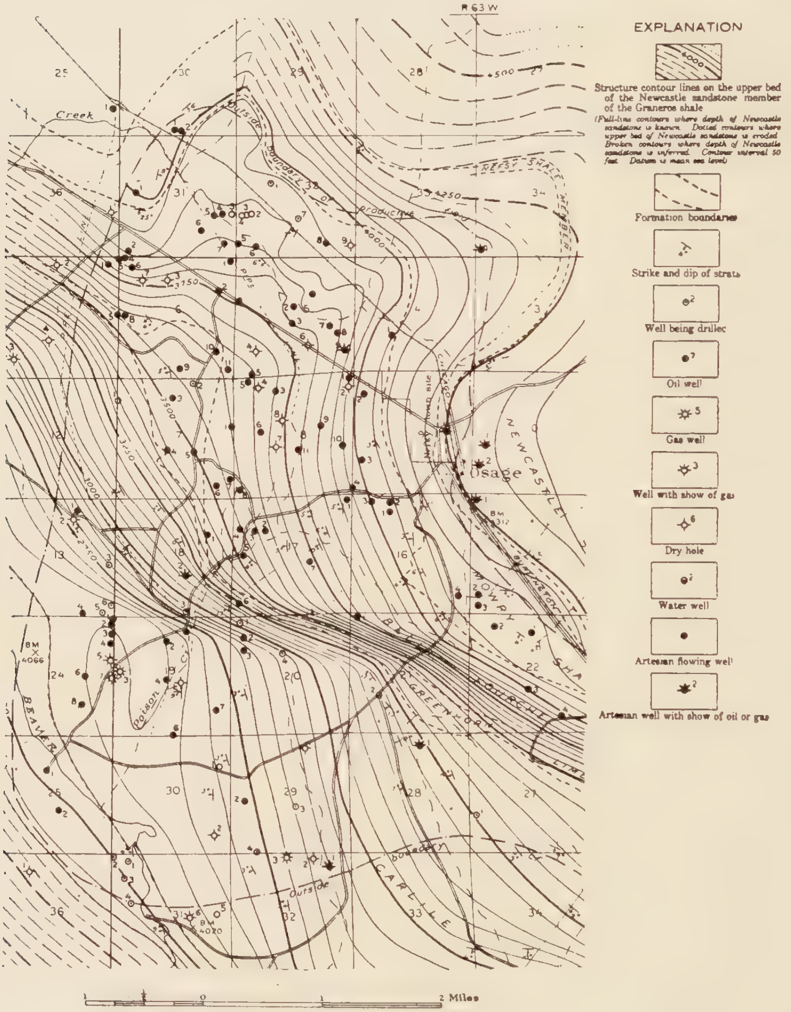

R 63 W
EXPLANATION
Structure contour lines on the upper bed of the Newcastle sandstone member of the Graneros shale
(Full-line contours where depth of Newcastle sandstone is known. Dotted contours where upper bed of Newcastle sandstone is eroded. Broken contours where depth of Newcastle sandstone is inferred. Contour interval 50 feet. Datum is mean sea level)
Formation boundaries
Strike and dip of strata
Well being drilled
Oil well
Gas well
Well with show of gas
Dry hole
Water well
Artesian flowing well
Artesian well with show of oil or gas
Creek
Outside boundary of productive area
Mowry shale
Newcastle
Osage
Belle Fourche
Greenhorn
Carlile
Beaver
Poison Creek
Pipe line
BM 4066
BM 4020
4500
4250
4000
3750
3500
3250
3000
2750
25
30
29
28
31
32
33
34
36
24
13
16
22
27
2 Miles

FIG. 68.—Structure map of the Osage oil pool, Weston County, Wyoming. After Collier, A. J.: U. S. G. S. Bull. 736, p. 89, 1922.

---

[1] Idem, p. 101.

TABLE 52.—GEOLOGIC FORMATIONS IN THE OSAGE OIL POOL ON THE EASTERN FLANK OF THE POWDER RIVER BASIN, WYOMING.*

System.	Series.	Group.		Formation and member.	Thickness (feet).	Character.	Oil possibilities
Tertiary(?).	Eocene(?).			Lance formation.	Not measured.	Massive cross-bedded light to buff sandstones, containing large sandy concretions of various shapes, and gray sandy shale. Fragments of dinosaurs and turtles.	
Cretaceous.	Upper Cretaceous.	Montana.		Fox Hills sandstone.	50±	Light-gray sandstone and sandy shale, with thin regular bedding, containing calcareous concretions in some places. Marine invertebrate fossils.	
				Pierre shale.	1,250±	Dark-gray clay shale, with indistinct bedding, containing many bands of calcareous concretions. Many invertebrate marine fossils usually contained in concretions. Prevailing forms *Baculites*, *Ammonites*, and *Inoceramus*.	This formation has yielded oil in the Salt Creek, Big Muddy, and Pilot Butte fields of Wyoming and flows of gas near Pierre, S. Dak., and Wray, Colo.
		Colorado.		Niobrara shale.	200	Light-yellowish to cream-colored calcareous shale, with some sandstone and impure chalk. Very readily distinguished wherever exposed by its light color	
				Carlile shale.	610	In upper part dark-gray shale, containing many bands of concretions, in lower part about 80 feet of shaly calcareous sandstone, probably the Wall Creek sandstone member. Marine invertebrate fossils and a 1-foot sandstone containing shark teeth in the lower part.	Showings of oil in lower part of formation in Osage field. Oil sand in Wakeman and Upton-Thornton fields.
				Greenhorn limestone.	100	Very fossiliferous shaly limestone at the top. Shale below contains several lines of calcareous concretions, also fossiliferous. At the base a second layer of shaly limestone in places.	Showing of oil near bottom of formation in one well.
			Graneros shale	Belle Fourche shale member.	560	Dark-gray shale. Calcareous concretions near the top; zone of Mowry-like shale about 100 feet below the top; many clay-ironstone concretions in lower part; thick bed of bentonite near base. Very few fossils.	Oil seep in upper part of member in Osage field. Showings of oil in several wells.
				Mowry shale member.	150	Hard light-colored siliceous shale; a fair road metal. Contains many fossil fish scales. Several thin beds of bentonite.	Showings of oil in wells in Osage field.
				Nefsy shale member.	25–50	Soft dark shale and thin sandy lenses	
				Newcastle sandstone member.	40–60	From one to four layers of sandstone separated by beds of shale, bentonite, and impure coal. The lower sandstone bed contains more or less coal in fragments. Called Muddy sand and Oil sand by drillers.	Principal oil sand of the Osage, Newcastle, and Moorcroft fields.
				Skull Creek shale member.	200	Dark-gray shale containing a few calcareous concretions. A stray oil sand 2 inches to 1 foot thick near middle. Siliceous shale near base. Very few fossils. Called Thermopolis shale by drillers, but represents only basal part of true Thermopolis shale.	Showing of light oil 100 feet below top in Osage field.
				Dakota sandstone.	50–100	Light-reddish sand and sandy shale, usually water sand. Upper Cretaceous fossil plants.	Showing of light oil in top of formation in Osage field. Heavy oil in Moorcroft field. Light oil in Lance Creek field.
	Lower Cretaceous.			Fuson formation.	30	Gray to red shale and thin sandstone.	
				Lakota sandstone.	200	Massive cross-bedded coarse sandstone, gray to buff, interbedded with shale. Lower Cretaceous fossil plants.	Principal oil sand in Mule Creek field.
Cretaceous (?).	Lower Cretaceous (?).			Morrison formation.	150	Massive buff, pale-green, and maroon sandy shale.	
Jurassic.	Upper Jurassic.			Sundance formation.	350	Greenish-gray and dark-gray shale, with thin limestone and buff sandstone. Many *Belemnites* and other fossils.	Possibly an oil showing in Moorcroft field.
Triassic (?).				Spearfish formation ("Red Beds")	500	Red sandy shale and soft red sandstone with beds of gypsum. No fossils.	The Chugwater formation of the Big Horn Basin, which is probably equivalent, in part, to the Spearfish formation, yields a small amount of oil.
Carboniferous.	Permian(?).			Minnekahta limestone.	40	Thin-bedded gray limestone. A few scattering small fossils.	Specimens collected in the Rocky Ford field have a fetid odor thought to be oil.
				Opeche formation.	75	Red sandy shale and shaly sandstone. No fossils.	
	Pennsylvanian.			Minnelusa sandstone.	600+	Hard white sandstone and buff and gray limy sandstone, more or less cross-bedded. Some thin beds of limestone and gypsum. Very few fossils.	Yields heavy oil in Rocky Ford field and Old Woman anticline, Wyo.
	Mississippian.			Pahasapa limestone.	700	Massive light-gray limestone. Very fossiliferous in places.	The Madison limestone, which is the Big Horn Basin equivalent of the Pahasapa, gives oil in the Soap Creek field, Mont.

* After Collier, A. J.: U. S. G. S. Bull. 736, p. 76, 1923.

the gas up to the shallow terrace. The cause may lie in the existence of minor faults or folds in the sand or in variations in porosity of local extent.

Osage pool has never been a center of great interest. The wells are all small. Yet it can hardly be doubted that a substantial amount of oil is present in the Newcastle sand. The bulk of it cannot be recovered with present methods because of the low gas pressure in all but a slightly domed section on the lower terrace and the areas immediately adjacent to it. Some tests report the Newcastle as water-containing. The water pressure is not comparable with that in the Dakota sandstone. The absence of steady artesian circulation and the general tightness of the sand are probably the explanation of the accumulation in an area that must be considered as having very little to favor it. The gravity of the oil, 39 to 40° Baume, indicates the absence of circulating waters with which reactions might occur. No seepages have been noted though the Newcastle sand outcrops.

A smaller section in which accumulation seems to have been caused by the same factors is found a short distance to the north in the Upton-Thornton pool.[1] There seepages have been found.

Broad Anticlinal Folds.—The terraced types of structures are generally small in size. Gas pressures are usually low and the production of the wells is seldom of the gusher type. Accumulation in such areas is due to local conditions, but the original movement of the oil and gas is initiated by structural conditions of a regional character. Thus accumulation in the terraces of Osage County in Oklahoma has resulted from eastward migration of the oil and gas up the slope of a westward dipping monocline. The same condition has existed in the Osage pool in Wyoming. Terrace accumulations in the Berea grit in southeastern Ohio have been made possible by the regional dip of the east flank of the Cincinnati Arch or geanticline.

It would be logical to expect that the crests of large and broad anticlinal folds would be areas in which it would be almost impossible to drill dry holes. Yet the arched areas of the geanticlinal folds are dotted with failures. The productive areas of the crest of the Cincinnati Arch are separated by non-productive ones of wide extent. Similarly the Bend Arch of Texas and the Sabine Uplift of Louisiana are productive in only a small portion of their total area. Production is limited to those sections in which variations in porosity or local structural conditions are most favorable. However, that does not mean that the geanticline is of no importance. Its regional dips determine the direction of movement. If continuous porous sands are present, they may be the cause of accumulation from points far distant from the final resting place of the oil or gas.

Where the crest of the strong fold is sharply defined as in the case of such structures as Salt Creek in Wyoming, Cushing in Oklahoma, and La Salle in Illinois, the accumulation of oil and gas follows closely the areas along the crest of the structure. The areas of these folds are large in comparison with the extent of the great majority of the world's producing structures. However, their areal extent is much less than that of the geanticlines mentioned. The author knows of only two instances in which continuous producing areas approach the areal extent of the true geanticline. They are the Monroe gas pool in northern Louisiana and the Panhandle gas and oil area in Texas. The bulk of the area of the second is gas containing, oil being restricted to areas on the flanks of the structure. The conditions in the Panhandle are of complex character, the producing zone being an unconformity. Because of this, discussion of the structure will be left to Chapter XVII.

---

[1] Hancock, E. T.: The Upton-Thornton Oil Field, U. S. G. S. Bull. No. 716, pp. 17–34, 1920.

Monroe Gas Pool, Louisiana.[1]—With the exception of the Panhandle section, the Monroe pool is the largest continuous producing area known. The area considered to be gas-bearing is placed at 350 square miles. It includes parts of Union, Morehouse, and Quachita Parishes. The area was discovered while being prospected for oil in 1916. The development lagged in the years immediately following because of the lack of a market for the gas. However, the development of the carbon black industry and the profitable extraction of casinghead gasoline led to rapid development in 1923 and in the years following. The area had only been partly drilled over by the end of 1926. The initial open flow of the gas wells averaged close to 10,000,000 cubic feet a day. One well was credited with 50,000,000 cubic feet.

While the gas rock, which is reached at depths of 1,940 to 2,220 feet below sea level, is not of the same thickness or porosity throughout the whole area, the absence of failures inside the contact between the gas and the water surface indicates that such differences are of minor importance. Intercommunication between all parts of the area, despite its size, appears to be possible. Bell has estimated the average effective thickness of the sand at 27 feet and the average porosity at 20%.

The structural outline of this immense pool is only approximately known, except in the areas of maximum development. The existence of a broad-topped dome to the northwest seems to be generally conceded. The dome changes into a broad southeastwardly plunging anticline. This southeastern portion has been the center of greatest development up to the present. Subsurface contours drawn upon this area show the top of the gas sand to be wrinkled in an irregular but minor manner. None of the wrinkles are of sufficient importance to divide the main body of the dome into gas and water areas, but they do affect the value of wells along the edge water line.

---

[1] Data on Monroe gas pool mainly from:

Bell, H. W.: Oil and Gas Journal, p. 58– , Feb. 4, 1926.

Stroud, Ben K., and Shayes, Fred. P.: A. A. P. G. Bull., Vol. 7, pp. 565–574, 1923.

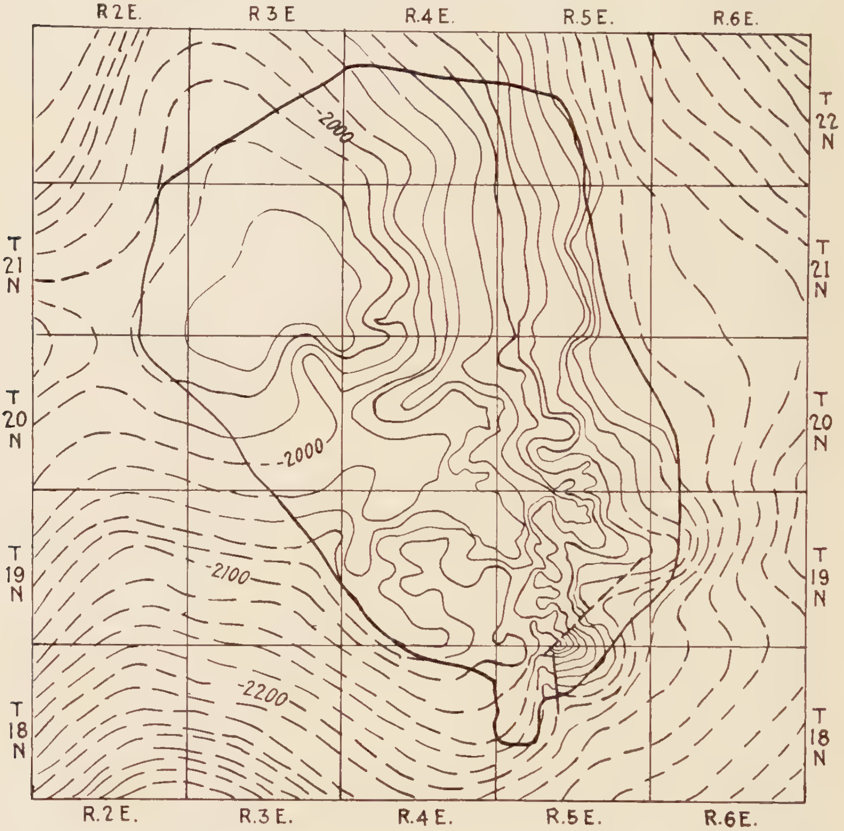


FIG. 69.—Structure map of the Monroe gas pool, Louisiana. Contours on top of "Gas Rock." Adapted from Wilson, J.: Oil and Gas Journal, Feb. 4, 1926, p. 58.

The productive horizon is a sandy portion of the Annona chalk formation. Some wells have also obtained gas from a second horizon about 200 feet below the first. No oil has been found in either sand, but the gasoline content of the gas is sufficient to warrant its recovery. The continuity of the main productive horizon is noteworthy.

One point that distinguishes the Monroe gas area from other large producing structures is the absence of steep dips. The distance from the center of the dome to the edge of production on the southeast is 18 miles, but the difference in elevation of the top of the main gas rock is only 200 feet. Broad-topped arches of this nature are more closely related to the large geanticlinal uplifts than to the sharp folds which are found at Cushing and Salt Creek.

Saddles.—The forces that cause the development of strong sharp folds are frequently applied unequally. Even if applied equally along a definite axis, the results may vary because of the differences in the character of the sediments that are being folded. Thus while areas may be arched as a whole, some of their portions may be arched more than others. These tend to take on a domal appearance. The sections between these especially arched areas are synclinal with respect to them. Yet they are anticlinal with respect to all of the other areas in the surrounding section. Contour maps show no definite synclinal closures. Because of their appearance when lying between strongly domed areas, these slight depressions have been called ''saddles.''

Where the amount of oil and gas is sufficient only to fill the distinctly domed portions of the fold, the saddle is normally water-bearing. This is true of the saddle between the two producing domes of the Cement anticline. Similarly it occurs in the First Wall Creek horizon in the saddle separating the Salt Creek dome from the Teapot dome (p.). In this sand, even the minor or Teapot dome is not of commercial importance as a producer. At Cushing (p. —) water occurs in the saddles, while oil is found in the domes in the so-called ''Bartlesville'' horizon. In other cases the saddles are highly productive. In a few they yield the oil, while the domes are mainly gas-bearing. This is true of several of the upper horizons at Cushing. In the Second Wall Creek horizon in the Salt Creek-Teapot structure, both the saddle and the main dome are containers of oil, but the Teapot or minor dome is largely a gas container.

The saddle is generally considered to be a low portion between domed areas having a single axis. The definition may be extended with justice to include low areas between folds having roughly parallel axis. This condition exists between the North and South Cochahee domes of the Pershing Pool in Oklahoma and between the Lamb and Torchlight anticlines in Wyoming. In the first, the low area contains oil; in the second, it is water-bearing.

Cement Anticline, Oklahoma.[1]—A strong fold known as the Cement anticline is located in Caddo County, Oklahoma. It lies on the north slope of the Wichita Mountains. Development began in 1916 with the discovery of a small gas well at 1,415 feet at a point off the center of the structure. The next year a large gas well was completed on the western of the two domes. Oil was discovered shortly afterward. The pool was never a large producer, the initial production of the wells being only about 100 barrels a day. However, the rate of decline was slow.

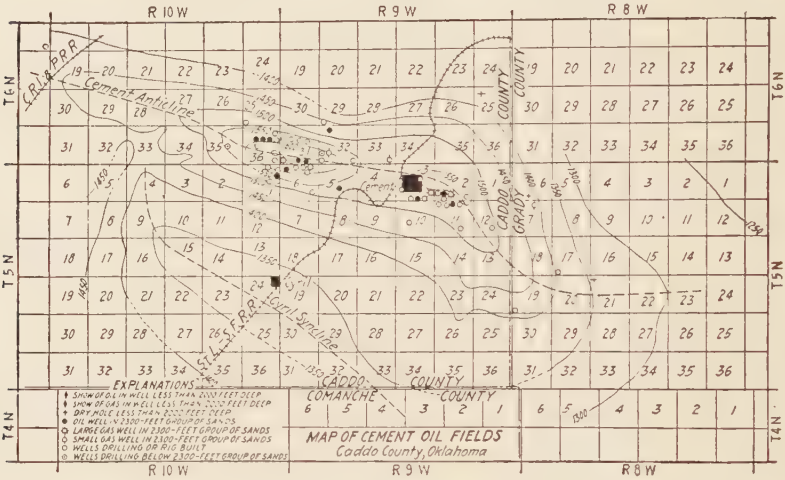

R 10 W
R 9 W
R 8 W
T 6 N
T 5 N
T 4 N
C.R.I.&P.R.R.
Cement Anticline
Cement
Cyril Syncline
St.L.S.F.R.R.
CADDO COUNTY
GRADY COUNTY
COMANCHE COUNTY
EXPLANATIONS
SHOW OF OIL IN WELL LESS THAN 2000 FEET DEEP
SHOW OF GAS IN WELL LESS THAN 2000 FEET DEEP
DRY HOLE LESS THAN 2000 FEET DEEP
OIL WELL IN 2300-FEET GROUP OF SANDS
LARGE GAS WELL IN 2300-FEET GROUP OF SANDS
SMALL GAS WELL IN 2300-FEET GROUP OF SANDS
WELLS DRILLING OR RIG BUILT
WELLS DRILLING BELOW 2300-FEET GROUP OF SANDS
MAP OF CEMENT OIL FIELDS
Caddo County, Oklahoma

FIG. 70.—Structural map of the Cement oil pool and adjacent area, Caddo County, Oklahoma. Contours on the Cyril gypsum bed. Interval 50 feet. After Clapp, F. G.: A. I. M. E. Trans., Vol. 65, p. 160, 1921.

The outcropping strata in the Cement area are beds of the Permian. These are considered to extend down to a depth of about 1,500 feet, but definite determination of the base is difficult. All of the producing horizons except one at 1,200 feet are considered to belong definitely in the Pennsylvanian. The bulk of the production has come from sands at 1,800, 1,850, and 2,300 feet. Deeper sands have shown some oil also. Some irregularities in the position of productive wells have been noted because of the lenticular character of parts of the sands.

---

[1] Data on Cement pool mainly from:

Clapp, F. G.: Geology of Cement Oil Field, A. I. M. M. E. Trans., Vol. 65, pp. 156–164, 1921.

Reeves, Frank: Geology of the Cement Oil Field, Caddo County, Oklahoma, U. S. G. S. Bull. 726-B, 1921.

However, the centers of production show close relationship to the structurally favored points. Thus most of the oil has been taken from the two distinct domes. The saddle area between them has been of minor importance. These areas are small in extent compared with the size of the whole anticline. The Cement anticline has a width of about two miles and may be traced for a length of 11 miles. South of it is the equally pronounced Cyril syncline; and north of it, the even larger Cobb syncline. The axes of these parallel the axis of the Cement anticline. The closure of the anticline as a whole, but excluding the two domes, is 60 feet in the outcropping beds. If the domes are included, the closure in one case is 120 feet and in the other 200 feet. The saddle is, therefore, a very definite one.

Torchlight and Lamb, Wyoming.[1]—Two of the older producing areas in Wyoming are found near the town of Basin in the eastern part of the Big Horn Basin. They were known as the Basin Field during part of their early history, but the names Torchlight and Lamb seem to be more generally used. The axes of these two anticlines are parallel, the Lamb anticline lying about one and one-fourth miles to the east of the Torchlight. Between them lies a structural depression 200 to 300 feet deep. No synclinal closure has been mapped, however. The two anticlines and the saddle area between them form the center of an arched area of considerable extent. The height of the closure is small compared with the vertical extent of closures in the majority of the folds in the Rockies.

Because of this the areas have not proved to be very efficient traps. This is especially true of the Lamb anticline, where the closure is only half of that on the Torchlight. The latter produced only 940 barrels of oil in 1926, about half of the wells originally productive having been abandoned. During a short period in 1915, about two years after development began, the production averaged between 800 and 1,000 barrels a day.

While some oil and gas have been obtained from other sands, the bulk of the oil has come from the Kimball sand and the gas from the Peay sand. The latter is in the Frontier and the former in the Mowry shale. Both of these formations are considered as belonging to the Colorado group of the Upper Cretaceous. The Kimball sand to the close of 1916 had been found productive in 30 wells on the Torchlight

---

[1] Mainly after:

Lupton, C. T.: U. S. G. S. Bull. 621-L, 1916; and Bull. 656, pp. 70–81, 1917.

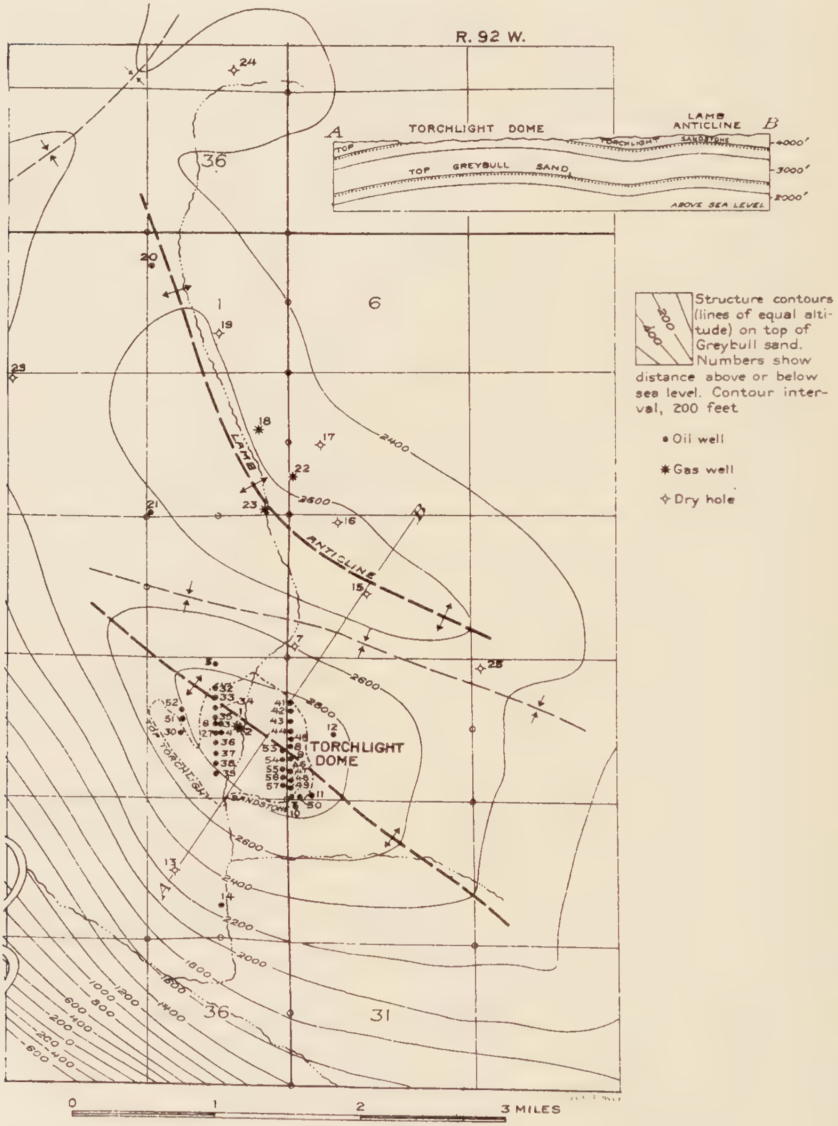


FIG. 71.—Structure contour map of the Lamb and Torchlight Domes. After Hewett, D. F., and Lupton, C. T.: U. S. G. S. Bull. 656, Plate IX, 1917.

structure but only in one on the Lamb. Of seven failures on the Lamb anticline only one reported the sand to be water-bearing. This would indicate that variations in porosity have had considerable importance in determining the exact position of the oil in this sand However, the small amount of oil and the gas that has come from that anticline has been obtained from the points which were most favored structurally. Wells drilled in the low depression between the two anticlines have failed to find oil or gas in any of the formations penetrated.

Pershing Pool, Oklahoma.[1]—The Pershing oil and gas pool is one of the larger producing areas in the east-central part of Osage County, Oklahoma. The development of the area began in 1906, but the wells drilled prior to 1918 showed only small amounts of oil or gas. The real development began with the discovery of a 390-barrel well in June of 1918. The area of the pool was rapidly outlined. By 1921 about 250 wells had been completed as oil producers, and about 15 were producers of gas only. The average initial production

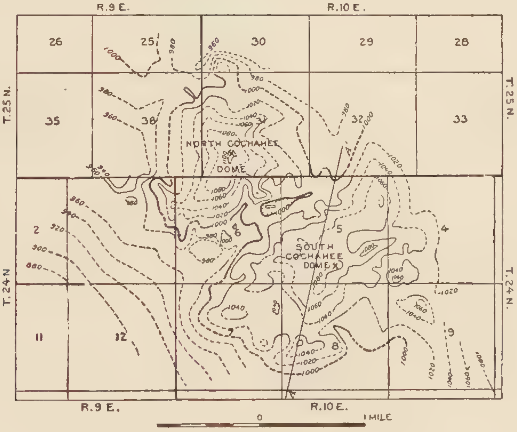


FIG. 72.—Structure map of the upper surface of the Pink lime in the Pershing oil and gas pool, Oklahoma. After Rubey, W. W.: U. S. G. S. Bull. 751–B, p. 38, 1923.

of the oil wells was a little less than 200 barrels a day. The gas wells averaged about 4,000,000 cubic feet.

Oil and gas have been reported at various depths in the pool. The chief of the sources is the Bartlesville sand found at a depth of about 2,000 feet. Above it some oil has been taken from the Layton sand, the Big lime, and the Oswego lime horizons. Below it the

---

[1] After Rubey, W. W.: U. S. G. S. Bull. 751–B, 1923.

Mississippi lime has yielded oil in a few wells. The Bartlesville sand is thick but apparently contains several breaks. The sand varies considerably in porosity. In some places this serves materially to lower the productivity of the wells which are most favorably located structurally. However, the position of the gas and oil is definitely in keeping with structural conditions. The areas of highest initial yield of oil are those lying close to the gas-covered portions of the structure.

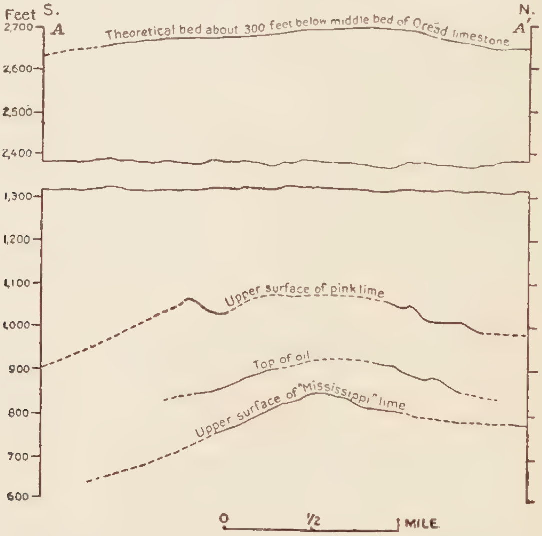

Feet
S.
A
N.
A′
2,700
2,600
2,500
2,400
1,300
1,200
1,100
1,000
900
800
700
600
Theoretical bed about 300 feet below middle bed of Oread limestone
Upper surface of pink lime
Top of oil
Upper surface of "Mississippi" lime
0
½
1 MILE

FIG. 73.—Cross section along line A–A′ of Fig. 72 Pershing Pool, Oklahoma. After Rubey, W. W.: U. S. G. S. Bull. 751–B, p. 43, 1923.

The two domes of the Pershing pool are closely related to the productive area of the Saucy Creek anticline, which lies to the northwest of them. The two domes lie upon a terrace-like area of irregular outline. Contours drawn on surface beds show distinct closures of only 20 feet in each of them. The South Cochahee dome is considerably larger in area than the North Cochahee dome. The rate of slope from its crest is smaller.

The irregular position of the oil-bearing portions of the Bartlesville horizon makes it difficult to contour. Because of this subsurface contour maps are frequently made upon the Pink lime, a definite marker horizon a short distance above it. In this the closure of both domes shows considerable increase vertically. It is most marked in the northern dome in which the closure is about 100 feet. The saddle between the two is much more pronounced and appears to have a true closure of very small extent. The form of the upper surface of the Mississippi lime has been contoured also. It shows the general outline of the upper horizons. Detailed mapping of this horizon was not possible because of the limited number of wells that had penetrated it.

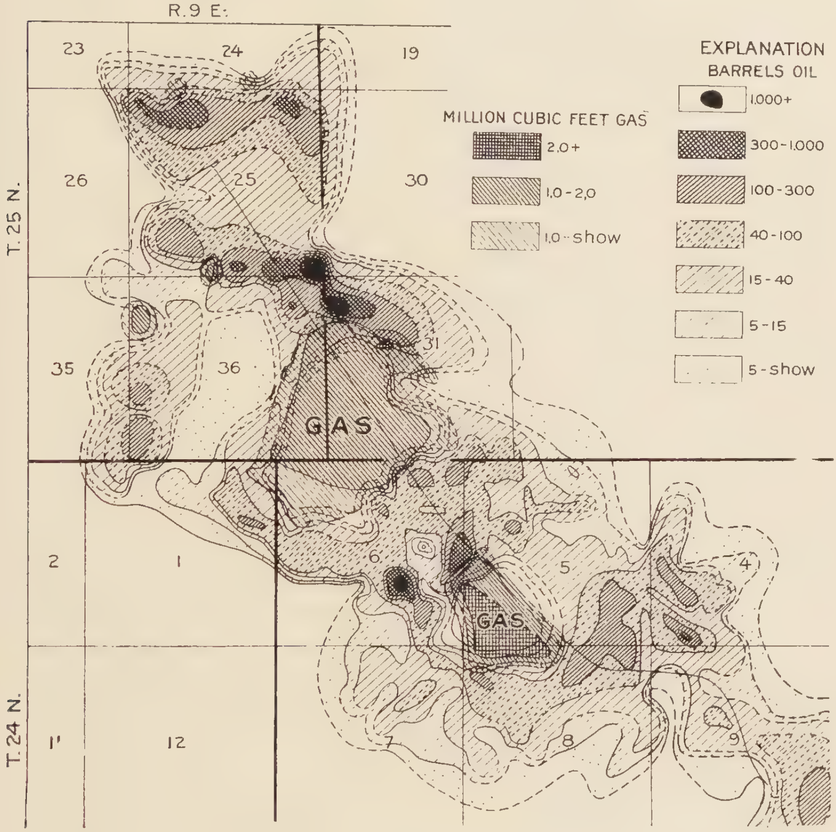


Fig. 74.—Chart of initial production of oil and gas in the Pershing pool, Oklahoma. After Rubey, W. W.: U. S. G. S. Bull, 751–B, Plate IX, 1923.

The gas area in the Bartlesville reflects the sharper folding of the northern dome, the greater portion of the gas being in that area. As is usual in the producing structures of the Osage, the eastern flanks of the domes are less productive than the western. This is altered somewhat by the presence of an area of tight sand immediately west of the North Cochahee dome. The whole of the saddle area, including the portion having the slight synclinal closure, is productive of oil. Some of the wells there yielded from 100 to 300 barrels initial production. The greater portion were of lower average yield.

Synclines.—Considerable has been written about production in synclines. Such areas might be expected to yield oil and gas where the horizons are devoid of water. Many have considered this condition to be present in some of the sands of the Catskill and related formations of Pennsylvania and West Virginia. The marked lenticularity of these sands and the variations in the porosity of even the thicker and more extensive horizons make it difficult to consider them as proving the condition suggested. Though the sands appear to be dry, there is no proof that they do not contain water in their capillary interstices. While the nature of the action is not known, the concentration of the brines in adjacent formations suggests that they are residual brines which have lost part of their original water content after their imprisonment. This casts doubt on the non-existence of water in other horizons at the time when the concentration of the oil occurred. The limited extent of the productive areas and the pressures under which the oil and gas appear to be held indicate that the particular porous sections in which they are imprisoned are of limited extent. If such is the case, the agency responsible for the concentration is probably capillarity; and the exact position, determined not by structural conditions, but by porosity variations.

The areas of the source material from which oil is derived are synclinal in form. Thus, while denying the probability of accumulation in local structures of synclinal nature, we must admit the importance of the regional syncline or the geosyncline in oil formation and accumulation. Where the flanks of such synclines are steep and water-flushing action has full play, only limited amounts of oil and gas should be expected near the center of the basin. The occurrence of oil and gas in commercial quantities can be expected only in the strongest folds. These are normally most pronounced along the rims of the basins where they have been subjected to the most severe thrusting action. Thus the bulk of the oil of Wyoming has come from strong folds on the rims of the structural basins.

Where the circulation has been sluggish or entirely lacking, the minor fold or the slight decrease in porosity may be sufficient to retard or entirely stop migration. Thus the Paleozoic synclines of the United States are spotted with producing pools.

The true syncline should be considered as having a form exactly the opposite of the true anticline. This would mean the existence of a definite basinal closure. Such areas are universally regarded by geologists as being the least desirable points in which to drill. Yet they have yielded oil in some sections where the horizons were known to be continuous and of uniform porosity. Close examination of the areas adjacent to such producing synclines shows them to be little more than saddles upon larger anticlinal folds. A very small area of this type is present in the saddle between the northern and southern domes of the Pershing pool just discussed. Production in such areas cannot be considered as being due to the synclinal condition. In fact, it may be said to occur despite that condition. Invariably it represents accumulation that is due to the influence of an adjacent anticlinal area.

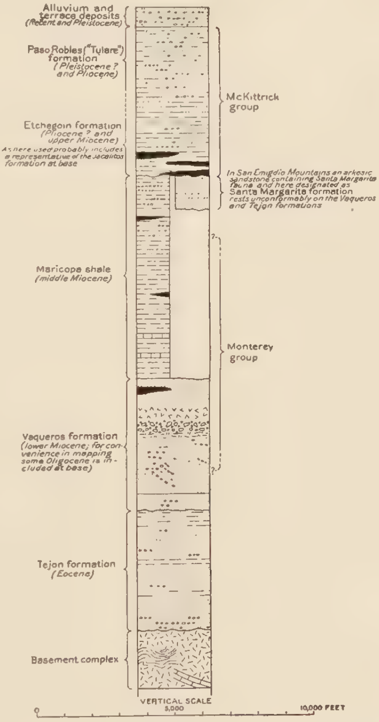

Alluvium and terrace deposits (Recent and Pleistocene)
Paso Robles ("Tulare") formation (Pleistocene? and Pliocene)
Etchegoin formation (Pliocene? and upper Miocene)
As here used probably includes a representative of the Jacalitos formation at base
McKittrick group
In San Emigdio Mountains an arkosic sandstone containing Santa Margarita fauna and here designated as Santa Margarita formation rests unconformably on the Vaqueros and Tejon formations
?
Maricopa shale (middle Miocene)
Monterey group
Vaqueros formation (lower Miocene; for convenience in mapping some Oligocene is included at base)
?
Tejon formation (Eocene)
Basement complex
VERTICAL SCALE
0
5,000
10,000 FEET

FIG. 75.—Generalized columnar section of the rocks in the Sunset-Midway oil district and in the north flank of the San Emigdio Mountains. Position of oil bearing beds indicated by solid black. After Pack, R. W.: U. S. G. S. Prof. Paper, No. 116, p. 21, 1920.

Probably the greatest single known accumulation of oil in a synclinal area is that contained in the Midway Valley syncline between the United-Honolulu anticline and the Spellacy-Midway anticline. This syncline is representative of a type that bears much the same relationship to the true syncline as the plunging anticline does to the true anticline. It has no true closure and may be considered to have the general form of half of a syncline. In the Midway Valley syncline the beds to the northeast and the southwest both slope toward a northwest-southeast trending synclinal axis. At the same time the axis itself rises to the northwest and plunges to the southeast. The productive area is limited to the northwestern or rising portion in which the synclinal area tends to merge with the anticlinal sections. This distribution of the oil in such structures is general. Because of it the author has used the expression "rising synclines" in describing such areas. They and saddles contribute the bulk of the so-called "synclinal" production.

Midway Valley Syncline, California.[1]—The Midway Valley syncline is a southeastwardly trending depression lying between the United-Honolulu anticline on the northeast and the Midway-Spellacy anticline on the southwest. It plunges to the southeast where it joins with the great synclinal area of the San Joaquin Basin. To the northwest it rises and merges with the Globe anticline, a broad flat-topped extension of the United-Honolulu structure. Thus while the axis of the rising syncline is more than 1,000 feet lower structurally than the crest of the Honolulu anticline at its southeastern end, there is practically no southeast dip along the range line between ranges 22 and 23 east.

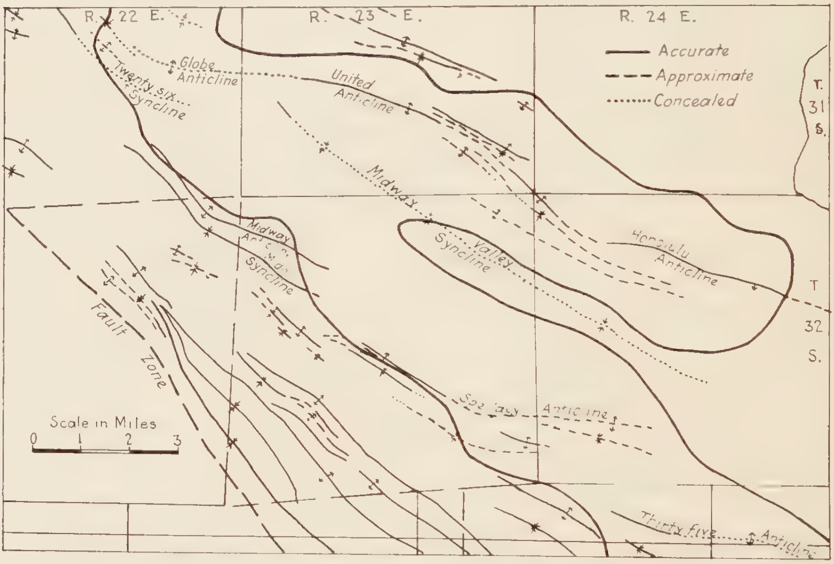


FIG. 76.—Sketch map showing position of productive areas in the Midway Valley Syncline and adjacent areas. Productive area enclosed by heavy line. Mainly from data by Pack, R. W.: U. S. G. S. Prof. Paper 116, 1920.

The deeper portion of the syncline is not productive of oil. The elevation of the northwestern portion is such that the oil has not only filled the distinctly anticlinal areas adjacent to it but has also spread into the synclinal area as well. The water line that surrounds the producing areas dominated by the United-Honolulu anticlines and known as Buena Vista Hills is not materially different from that which separates the oil from the water-containing areas in the syncline.

---

[1] After Pack, R. W.: The Sunset-Midway Oil Field, California, U. S. G. S. Prof. Paper 116, 1920.

The producing horizons in the area are a series of thick sands lying at the top of the Maricopa shales. They are divided into three zones. The upper or A zone is productive in the Spellacy anticline on a small scale. The B zone is productive in both the Spellacy-Midway and the United-Honolulu anticlines. It is water-bearing in the syncline, however. The C horizon is much more extensive as an oil container than the upper zones. It is the only one in which oil is found in the synclinal area in commercial amounts. Water sands have caused very little trouble in the Buena Vista Hills in this horizon, but water has been encountered immediately under the oil in the top of the zone in the syncline and has proved extremely difficult to handle.

A number of wells having large initial yields have been completed in the synclinal area, but the relatively thin body of oil sand above the water has not been conducive to sustained production like that obtained in the adjacent anticlinal areas. The productivity of this rising syncline may be considered as due solely to the excess of oil over the amount that could be stored in the porous beds of the adjacent anticlines.

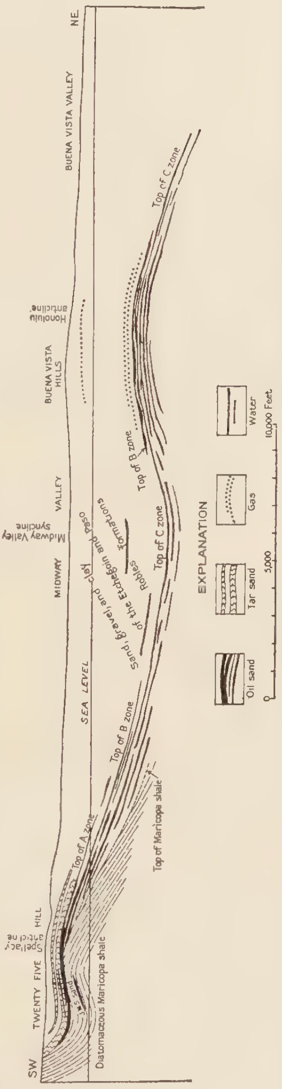


FIG. 77.—Geologic cross section through the Midway area, with particular reference to the position of the Midway Valley syncline. After Pack, R. W.: U. S. G. S. Prof. Paper 116, p. 78, 1920.

Asphalt Sealed Traps.—Where beds are continuous to their outcrops and have been subjected to tilting but not to folding, the escape of oil and gas is usually rapid. During the movement of the oil toward the outcrop, it comes in contact with surface waters. These frequently have high contents of sulphates and other active salts. If the oil is of low viscosity and is composed mainly of paraffin or other chemically inactive hydrocarbons, little or no reaction between the salts of the water and the oil may be expected. The escape of the hydrocarbons is not subjected to any retarding influences. Where the oil contains a high percentage of the more viscous and unstable types of compounds, reactions may occur which result in the development of tarry and semi-solid asphaltic substances. These clog up the interstices of the porous rocks through which the oils have been migrating. At first the action may be limited to retarding the movement, but later the seal may become sufficiently effective to stop all movement toward the outcrop.

The distribution of asphalts and asphaltic matter in sands suggests that the amount of the salts needed for the conversion of oils into asphaltic semi-solids can only be supplied when there is constant addition of new waters. This implies the existence of artesian circulation. This is pronounced in some of the Tertiary and Cretaceous areas. It does not appear to have ever been of great importance in those areas where the Paleozoic beds are productive in the Mid-Continent and the Eastern Provinces. It is probably an explanation of the high densities and viscosities of the oil contained in the Late Paleozoic and Early Mesozoic horizons of central Wyoming.

Asphalt seals are usually not strong enough to cause permanent accumulations of oil and gas down the slope from them. They may delay the escape of the oil to such an extent that it is converted into asphalt over wide areas. This seems to have occurred in a number of places in the upper horizons of California and other areas producing from the Tertiary. In a few cases the amount of oil trapped behind the asphaltic seal has been so large in amount that its alteration has not been completed. It remains as liquid oil and may, because of the great breadth of the asphaltic material adjacent to the outcrop, be under considerable gas pressure. The oil in such areas is invariably of asphaltic nature, high in sulphur, and heavier and more viscous than the oils of the same age and horizon found at points distant from the outcrop.

Sunset Area, California.[1]—A condition of the type just described is found in the vicinity of Fellows, immediately east of the axis of the Midway anticline. At the outcrop, the productive beds, a series of sands and shales lying above the Maricopa shale, are saturated with asphaltic matter. In the region near the outcrop the productive horizon is about 400 feet thick. To the east the shales between some of the sandy portions become thicker and the horizon is divided into three zones. Both of the upper zones are productive for only a short distance, the free oil giving way to tar or asphaltic sands and then to water sands. The lowest or C zone is productive for some distance, the oil extending into the Midway syncline.

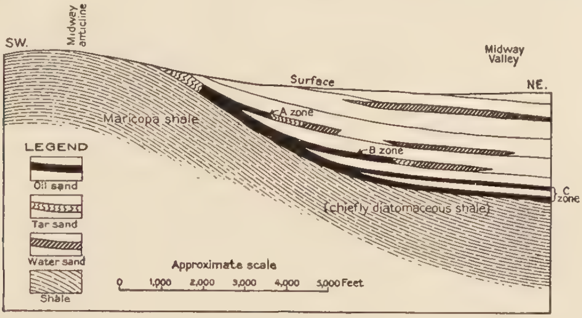


FIG. 78.—Diagram showing relations of productive oil zones and tar horizons in the vicinity of Fellows (Sunset area), California. After Pack, R. W.: U. S. G. S. Prof. Paper 116, p. 115, 1920.

Despite the nature of the seal, the area has been a very substantial producer. Many wells have been difficult to control because of their size and high gas pressures. Some have had initial yields of from 1,000 to 3,000 barrels a day. The oil averages from 14 to 18° Baume gravity; that in adjacent non-outcropping areas, from 21 to 28°. While the asphaltic matter has undoubtedly been a major factor in causing the accumulation, some importance must be attached to the thinning of the sandy portions in zones B and C toward the west. These were laid down upon an eastward sloping surface of the Maricopa shale and tend to die out to the west. It should be pointed out that this condition has been found to exist in the nearby Sunset Extension pool, which is discussed on page 355.

Overturned Folds.—Folds having inclined axes are of major importance as areas of oil accumulation. Those in which the folding has proceeded to the point where the structure can be considered as overturned are of minor importance. Structures of this type have been identified in Galicia, and such folding is considered to accompany the salt-cored structures of Roumania. In most cases, however, folds of this type have proved to be of little interest. One unusual condition in which production has been obtained from overturned folds that have been sealed by asphaltic material has been reported by Arnold and Johnson. This section is one of marked folding and lies south of an overthrust fault area in the McKittrick district in California. The faulted area is discussed on page 335.

---

[1] After Pack, R. W.: The Sunset-Midway Oil Field, California, U. S. G. S. Prof. Paper 116, 1920.

McKittrick Overturned Fold, California.[1]—The series of closely related overturned folds lying in the McKittrick district were produced by severe thrusting action from the west. The axes of the folds are inclined to the west at low angles. Since the time when the original accumulation of the oil took place, the upper portions of the folds have been removed by erosion. The hypothetical section drawn by Arnold and Johnson shows the form of the remaining beds. The portions of the productive beds lying close to the surface have been exposed to the entrance of surface waters. Some oil has escaped and formed brea deposits on the surface. Some still contained in the sands has been converted into tarry matter and, with the brea, has served to prevent the escape of the rest of the oil. While oil is found fairly close to the outcrops in several places, the bulk of the larger wells have obtained their production in the deeper parts. The largest single area of rich sand was found to correspond with the location of a small anticlinal area in a synclinal fold.

Summary.—At best asphalt traps, such as those which are considered to be responsible for part of the accumulation at McKittrick and for the area near Fellows, are only temporary in their retentive power. It would appear that the same can be said of the low terraced types of structures in areas of high dips and water circulation. The terraced structures are of greatest importance in areas of low dips and stagnant waters. Synclinal areas may contain oil or even gas, but the presence of these substances is apparently due to factors other than the synclinal structure. The strong sharply outlined anticlinal fold must be considered as the most desirable area for testing in every section where such folds are present in association with weaker folds.

[1] Arnold, R., and Johnson, H. R.: Preliminary report on the McKittrick-Sunset oil region, Kern and San Luis Obispo Counties, Cal., U. S. G. S. Bull. 406, 1910.

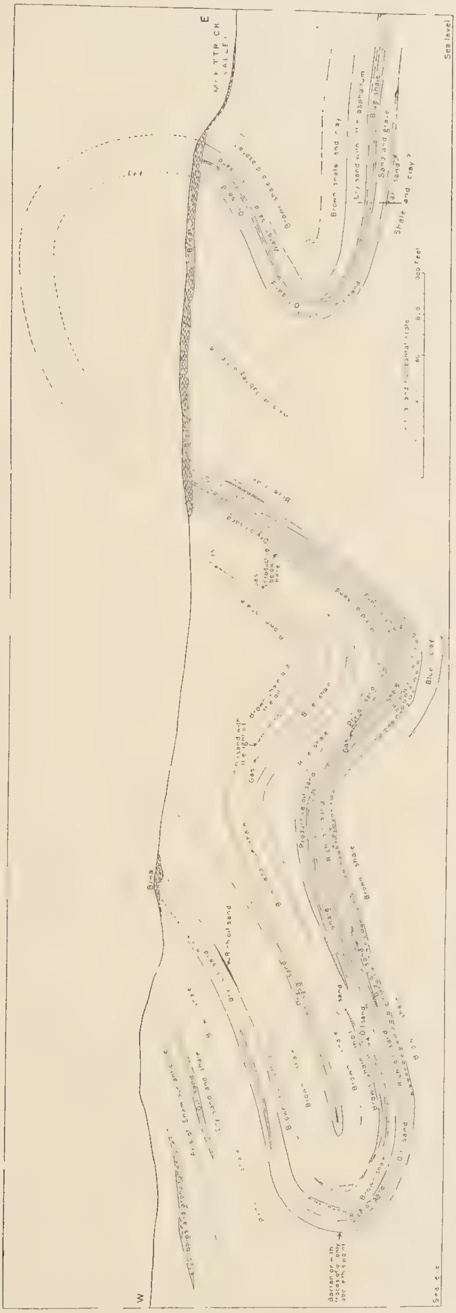


FIG. 79.—McKittrick overturned fold. Hypothetical section. After Arnold, R., and Johnson, H.: U. S. G. S. Bull. 406, p. 130 insert, 1910.

Such folds have a variety of forms varying with their origin. The contact between water and oil may not be always of the same structural elevation because of circulation of the water and the differences in the amount of accumulation from different directions In some areas the quantity of oil present is not sufficient to fill more than the highest domal areas. In others it fills all of the closures and extends into adjacent areas.

In discussing the accumulation of oil on strong folds, distinction must be made between folds of geanticlinal proportions and those of local extent. The strong local fold has a distinct axis or crest. It may contain several saddles and domes, but its production is closely related to the crest. The geanticlinal fold is usually of broad outline. Its crest is not clearly defined, and its productive areas are likely to be determined by small local foldings or sand variations.

CHAPTER XIII.

STRUCTURES DOMINATED BY FAULTING.

Faults are present in most of the producing anticlines in strongly folded areas. They are frequently of major importance in initiating or assisting the movement of oil and gas from one stratum to another. Within the larger producing folds they frequently determine the areas of maximum production. In some they tend to isolate producing areas within the major fold. It is seldom, however, that the fault itself can be considered as the primary cause of the accumulation.

This is particularly noticeable in sections where small disconnected faults are the only types present. The normal or gravity fault is usually of such small extent both vertically and horizontally that it has little permanent effect upon the migration of oil and gas. This is especially true in formations in which there is any circulation of the waters present. Strong dips are also likely to decrease the chances of accumulation along the normal fault of small size. Minor faults of such character have been reported as causes of accumulation at various points in the Mid-Continent and Appalachian Provinces. In these, the circulation of the waters is less than in any of the rest of the world's major areas. Similarly the dips of the producing horizons are extremely low. Yet it is difficult to point to areas in which production of any importance can be said to have been caused solely by faulting action.

The normal fault, having its strike parallel to the dip of the strata which it crosses, interposes no barrier to the movement of oil and gas through porous beds up the dip. If the fault plane is parallel to the strike of the beds and has its downthrown side on the basin-ward slope of the beds, it is effective only in the absence of sufficient slope in the beds adjacent to the fault to permit the oil and gas to move around the ends. If circulating water is present, the trap is even less effective. Where the downthrow side is away from the basin and the beds facing it on the upthrow portion are arched, the chances of retention are considerably greater. Such arching is seldom sufficiently pronounced in this type of faulting to be permanent in its effects.

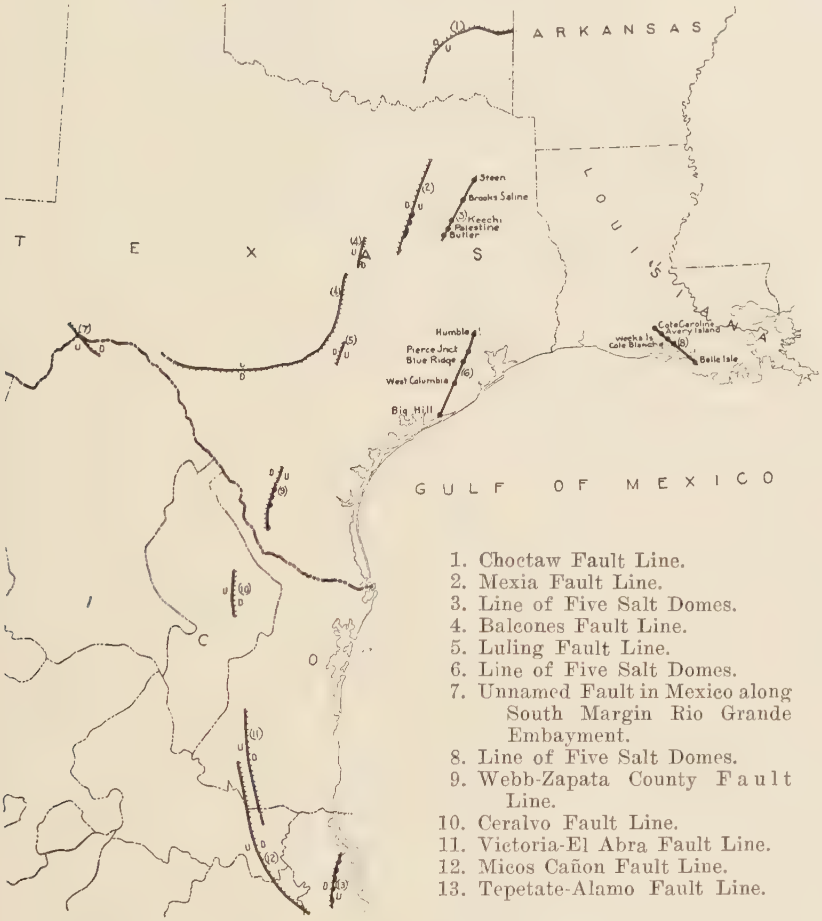
Much the same may be said of the small faults resulting from compression. In these, however, the actual faulting action is commonly preceded or accompanied by folding. In fact, if we exclude from our minds the fault-like movements of the zone of shear, we may consider the compression fault as a special type of fold.

Small faults are looked upon with disfavor not only because of their inadequacy to prevent migration unless of unusual form but because of the marked tendency for them to die out with depth. This is especially evident in the gravity type of fault. Some compression faults show the same tendency. This is usually less marked, however, and geologists would look at such faults with more favor if they could be definitely identified from surface data. This is possible in some cases, but in most the poor character of the outcrops available for study and the nearly vertical position of the fault planes make this difficult.

From this brief discussion it may be inferred that production is of rare occurrence along such fault lines from strata in which the accumulation is due solely to the faults. This is true of the productive areas discovered up to the present. The minor fault seldom yields sufficient oil to pay for the cost of its testing. However, not all faults can be classed as minor types. Where the fault is of such size that it can be traced for a number of miles along the strike of the beds, accumulation may be of great value. In such areas the circulation of the waters of the oil-containing horizon is materially lessened. The distance to the ends of the fault retard the chance of escape around them and increase the possibility of the oil becoming concentrated in minor folds in the strata along the fault line. Because of this, major fault zones, whether of normal or compressional origin, are areas which should be subjected to the closest study.

Luling-Mexia and Balcones Fault Zones.—These systems of faults and their southern extensions into southern Texas and eastern Mexico are the dominating feature of the transition from the Paleozoic and other old rock areas of the Llano and related uplift areas of Texas and northern Mexico, and the younger sediments to the east and south of them. Structurally, the roughly arc-shaped Balcones fault is the best known of these. At points it has a maximum throw of 1,000 feet with the downthrow to the east or basin-ward side. The fault line is apparently of considerable age and has been a center of movement for some periods. The movements were intermittent, the last, though possibly not the most important, occurring during the Pliocene.

A system of faults closely related to the Balcones line is found in Mexico. These have a general north-south trend except in the extreme south where they shift to the southeast. The displacement in these is of greater intensity, the drop to the east being measured in thousands of feet. These faults are known as the Ceralvo, the Victoria-El Abra, and the Micos Cañon faults. The last two are parallel to each other for some distance. All of these faults are gravity faults. None of them produce commercial quantities of oil at present.



1. Choctaw Fault Line.
2. Mexia Fault Line.
3. Line of Five Salt Domes.
4. Balcones Fault Line.
5. Luling Fault Line.
6. Line of Five Salt Domes.
7. Unnamed Fault in Mexico along South Margin Rio Grande Embayment.
8. Line of Five Salt Domes.
9. Webb-Zapata County Fault Line.
10. Ceralvo Fault Line.
11. Victoria-El Abra Fault Line.
12. Micos Cañon Fault Line.
13. Tepetate-Alamo Fault Line.

Fig. 80.—Map showing structural features of the Gulf Coastal plain. After Pratt, W. E., and Lahee, F. H.: A. A. P. G. Bull., Vol. 7, p. 228, 1923.

A series of roughly parallel fault zones to the east of this large group has proved highly productive. These are the Mexia fault zone, the Luling fault, the inferred Webb-Zapata County fault line, and the Tepetate-Alamo fault line. In each of these the major throw is to the west and the productive area on the east. The faults of the Luling-Mexia zone are the best known of this group. They have been outlined more fully by the drill than the others and are in general more easily worked out. The throw in this section is not more than half of the throw of the Balcones line to the west of it.

Except in one case no production has been obtained west of the main fault line of the Mexia zone. This was the discovery of a small pool at Nigger Creek three and one-half miles west of Mexia pool on a subordinate fault known as the Tehuacana fault. The fault is parallel and similar to the Mexia fault, but it is smaller and has a limited drainage area.

Like the Balcones and related fault zones, the faults of this productive belt are all considered to be of the normal type. They are evidently the results of reactions in the underlying, deeply buried competent and shear zones following the very intense downfaulting to the west of them. They have in some cases the appearance of faulted upfolds.

The Mexia Fault Zone.[1]—Production in the general area of the Mexia fault zone may be said to date back to 1896 when the Corsicana pool was discovered. The oil came from wells of about 1,000 feet depth. The section developed rapidly considering the absence of other producing areas in Texas at the time. It reached its maximum production with 763,424 barrels in 1901. In 1900 oil was discovered in the Powell area six miles due east of Corsicana and also in the sections between. This area was productive of a heavier grade of oil and gave a crest production of 673,221 barrels in 1906. The two sections, while not large sources, were the main ones from which that portion of Texas obtained its gas for many years. In 1913 the Mexia-Groesbeck area to the south was opened up as a substantial source of gas.

---

[1] Data on the Mexia fault zone mainly from:

Hill, H. B., and Sutton, C. E.: Summarized Engineering Report on the Powell Field, Navarro County, Texas, with Special Reference to Water Problems and Corrective Work, Pet. Dev. and Tech. in 1926, pp. 297–320.

Lahee, F. H.: The Currie Field in Navarro County, Texas, A. A. P. G. Bull., Vol. 7, pp. 25–36, 1923.

Lahee, F. H.: Comparative Study of Well Logs on the Mexia Type of Structure, A. I. M. M. E. Trans., Vol. 71, pp. 1329–1350, 1925.

Lahee, F. H.: The Wortham and Lake Richland Faults, A. A. P. G. Bull., Vol. 9, p. 172, 1925.

Lahee, F. H.: Further Notes on the Origin and Nature of the Currie Structure, Navarro County, Texas, A. A. P. G. Bull., Vol. 10, pp. 61–71, 1926.

Matson, G. C.: Gas Prospects South and Southeast of Dallas, U. S. G. S. Bull. No. 629, pp. 77–118, 1916.

Matson, G. C., and Hopkins, O. B.: The Corsicana Oil and Gas Field, Texas, U. S. G. S. Bull. No. 661, pp. 211–252, 1918.

Pratt, W. E., and Lahee, F. H.: Faulting and Petroleum Accumulation at Mexia, Texas, A. A. P. G. Bull., Vol. 7, pp. 226–236, 1923.

The productive horizons in the different sections were not considered to be of exactly the same age, but all were in the latest sediments of the Upper Cretaceous. The gas of the Mexia-Groesbeck area and the oil of Powell were placed in the Navarro formation, while the lighter oil of the Corsicana pool was believed to come from the underlying Taylor marl. The sands were typical sandstones, those in the Taylor being somewhat lenticular in character and inclined to be calcareous. The Corsicana and Powell areas showed production from a number of relatively small anticlines on a gently southeastward dipping monocline. The Mexia-Groesbeck gas was taken from a very narrow and strongly developed anticlinal fold having its axis parallel to the general strike of the beds in the area.

The sensational development that made the area one of the foremost

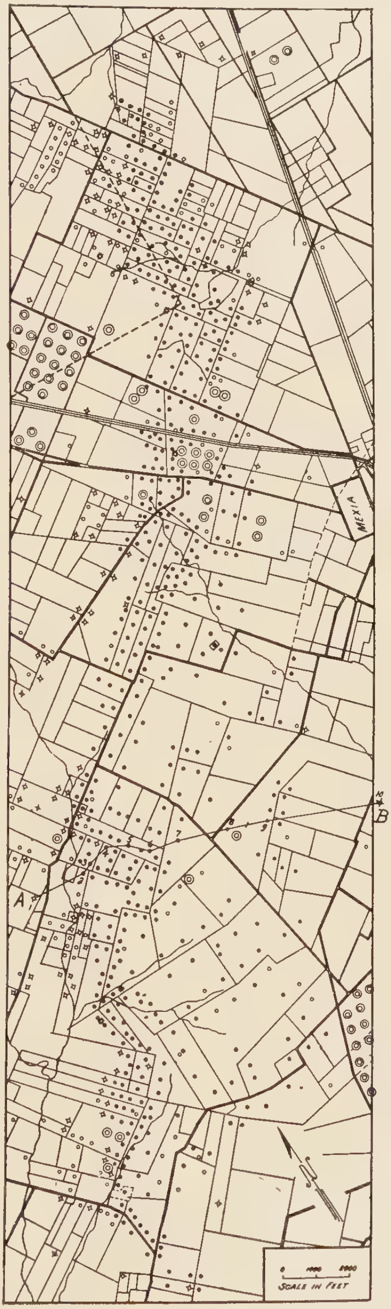


FIG. 81.—Sketch map of the Mexia oil pool. After Lahee, F. H.: A. I. M. M. E. Trans., Vol. LXXI, p. 1332, 1925.

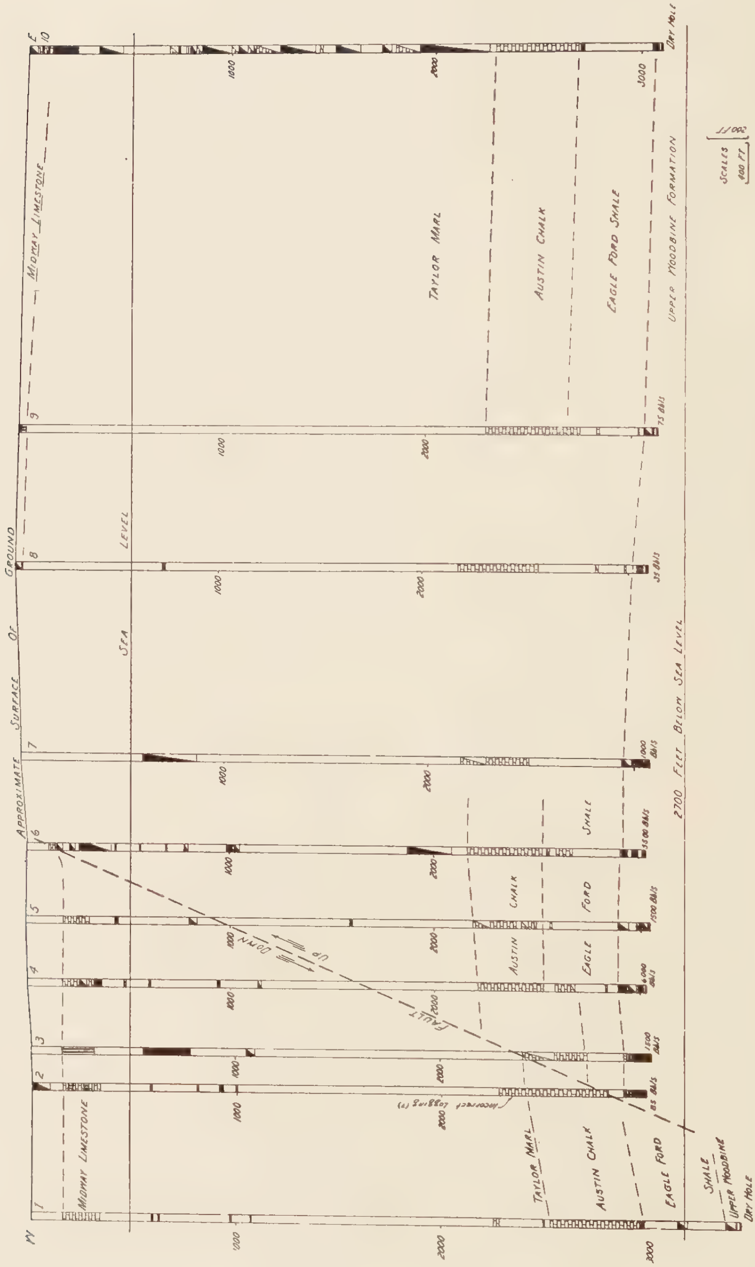


FIG. 82.—Vertical section across the Mexia pool along the line A–B of Fig. 81. After Lahee, F. H.: A. I. M. M. E. Trans., Vol. LXXI, p. 133, 1925.

producing districts of the world started in 1921 with the discovery of oil in the Woodbine formation at Mexia. Drilling that followed this discovery disclosed small quantities of oil at Kosse, Thornton, and Groesbeck to the south of Mexia, and brought the development of a moderately large pool at Currie to the north. In 1923 deep wells at Powell demonstrated the existence of a pool similar in importance to the Mexia discovery. In the year following Richland and Wortham were discovered. Richland was only a moderate sized pool, but Wortham proved to be of considerable size though less important than Mexia and Powell. By the end of 1926 Powell had produced more than 90,000,000 barrels of oil; Mexia, slightly less than 80,000,000; and Wortham, nearly 20,000,000.

The zone in which these pools lie appears to be dominated by a series of closely related parallel en échelon faults. The trend of the fault zone is from 20 to 30 degrees east of north. The displacement is between 200 and 400 feet with the downthrow on the west side. The surface reflections of the faults are not marked, the faulting being less intense in the surface beds and partly covered by soils and recent alluvial deposits. Some surface work was possible, however, Alexander Deussen[1] noting and suggesting the importance of the fault at Mexia as early as 1914. The

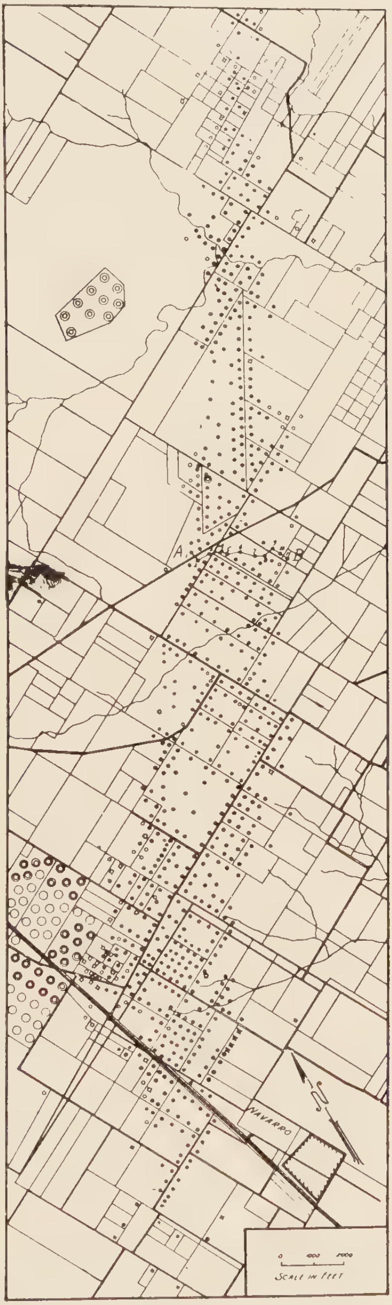


FIG. 83.—Sketch map of the Powell oil pool. After Lahee, F. H.: A. I. M. E. Trans., Vol. LXXI, p. 1336, 1925.

---

[1] U. S. G. S. Water Supply Paper 335, p. 301, 1914.

displacement in the surface Midway strata is only 100 to 150 feet at points where the Austin chalk shows its maximum downthrow of 400 to 500 feet. Part of this difference is attributed to lessening of the displacement in passage through the soft and yielding Taylor and Navarro formations which separate the Midway and the Austin. It is also possible to consider that the faulting either occurred in part previous to the deposition of these sediments or was partly simultaneous with their deposition.

The fault planes are not vertical but usually show dips of from 45 to 65 degrees to the west. While there is no intense folding, there is evidence of drag accompanying the faulting. This has given rise to slight anticlinal arching to the east of the fault. This arching is not continuous and has assisted in localizing the areas of accumulation. The main agency in causing accumulation, however, is the faulting itself.

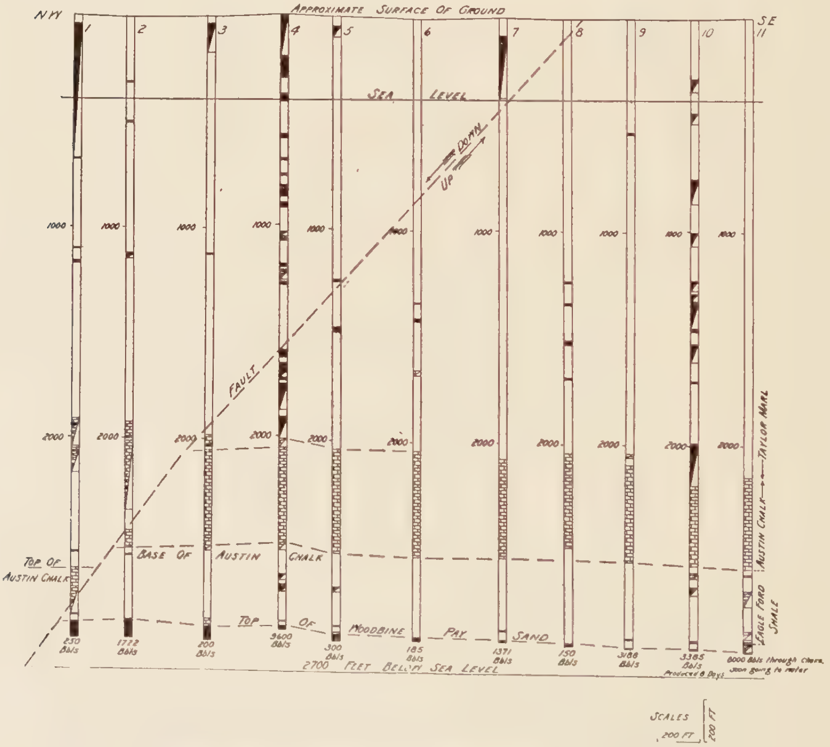


FIG. 84.—Vertical section across the Powell pool along the line A–B of Fig. 83. After Lahee, F. H.: A. I. M. M. E. Trans., Vol. LXXI, p. 1337, 1925.

As might be inferred from the intensity of the throw and the angle of the displacement, the outline of the structurally desirable areas in the Woodbine is far from identical with that which is indicated in the surface beds. Generally the productive area lies some distance to the west, in some places as much as half a mile. This was of extreme importance in the development because of the narrowness of the productive belts. The discovery well at Mexia was located close to the surface axis but proved to be upon the eastern edge of the producing area. This pool is the largest in extent of the group. It extends parallel to the fault for a distance of seven miles. On the west side it is limited by the fault; and on the east side, by water. Its maximum width before any encroachment of edge water was one and one-fourth miles. Powell, a larger producer, is of approximately the same length but only reaches a width of 4,000 feet. The smaller pool at Currie is only two miles long and has a maximum width of 2,800 feet. Wortham was somewhat longer but extremely narrow, being only 2,000 feet in width at its broadest point.

Production in these important pools has come entirely from the Woodbine formation. Several sands separated by measurable thicknesses of shales have been found, but they were so closely related in position that their development was practically simultaneous. Flush productions of 4,000 and 5,000 barrels were not unusual during the development of the pools. This was due in part to gas pressure and in part to the high pressure of the edge water throughout every part of the area. Most of the wells have yielded considerable water ever since the gas pressure was reduced during early operations.

Deeper production has been sought in a number of tests. Some short-lived production was obtained from the Edwards limestone at Kosse. The Trinity sand is believed to underlie the section and may prove productive. As the depth to the Woodbine is between 2,850 and 3,000 feet, the estimated depth to the Trinity is 5,500. Should oil be found in narrow pools similar to those of the Woodbine at such a depth, the cost of exploration would be extremely high.

The Luling Fault.[1]—The Luling pool is located partly in Caldwell

---

[1] Data on the Luling fault mainly from:

Brucks, Ernest W.: The Luling Field, Caldwell and Guadalupe Counties, Texas, A. A. P. G. Bull., Vol. 9, pp. 632–654, 1925.

Sellards, E. H.: The Luling Oil Field in Caldwell County, Texas, A. A. P. G. Bull., Vol. 8, pp. 775–788, 1924.

Sellards, E. H.: The Producing Horizon in the Rios Well in Caldwell County, Univ. Texas Bull., No. 2239, 1922.

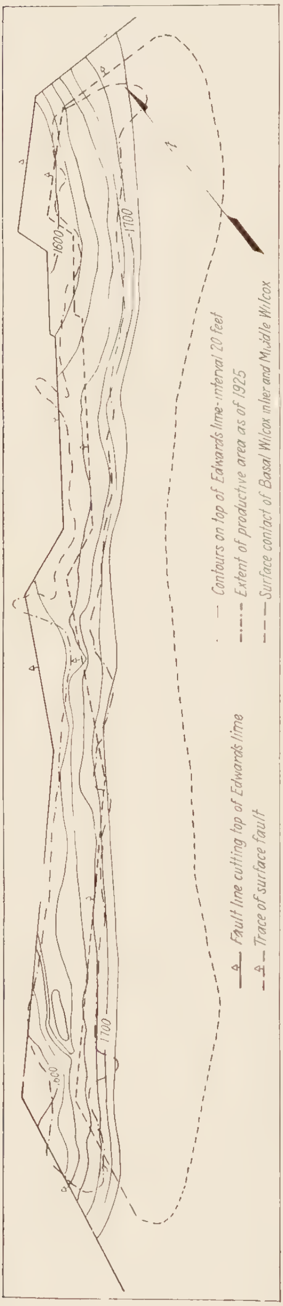

-1600
-1700
-1700
-1600
Contours on top of Edwards lime-interval 20 feet
Extent of productive area as of 1925
Surface contact of Basal Wilcox inlier and Middle Wilcox
Fault line cutting top of Edwards lime
Trace of surface fault

FIG. 85.—Structure map of the Luling pool. Contours on the top of the Edwards limestone. Adapted from Brucks, E. W.: A. A. P. G. Bull., Vol. 9, p. 635, 1925.

and partly in Guadalupe Counties in Texas. It is a typical normal fault structure. The Luling fault zone, which is responsible for the accumulation, lies parallel to the main, Balcones fault zone but is 20 miles to the southeast of that zone. The discovery well was drilled in 1922 after several tests had been drilled that showed only small quantities of oil. As outlined in 1925, the pool had a length of seven and one-half miles along the strike of the fault and a maximum width of 3,000 feet. Because of the absence of competitive drilling, the pool did not develop as rapidly as those in the Mexia zone. However, at the end of 1926 the cumulative production had passed the 20,000,000 mark.

The discovery well was based upon the surface trace of the fault and the exposure of early Wilcox beds as an inlier surrounded by later Wilcox. The formations throughout the area, except close to the fault, have a general southeast dip of one or two degrees. The fault is not a single one but consists of a group of closely related parallel ones, connected at the ends by transverse faults. The trend or strike of the main fault line is north 35 degrees east. The faults dip to the west at an angle varying from 48 to 65 degrees. When the Edwards limestone of the Lower Cretaceous, in which the oil is contained, is reached, the heave is between 1,000 and 1,800 feet to the northwest. The vertical displacement in the main fault is between 450 and 500 feet.

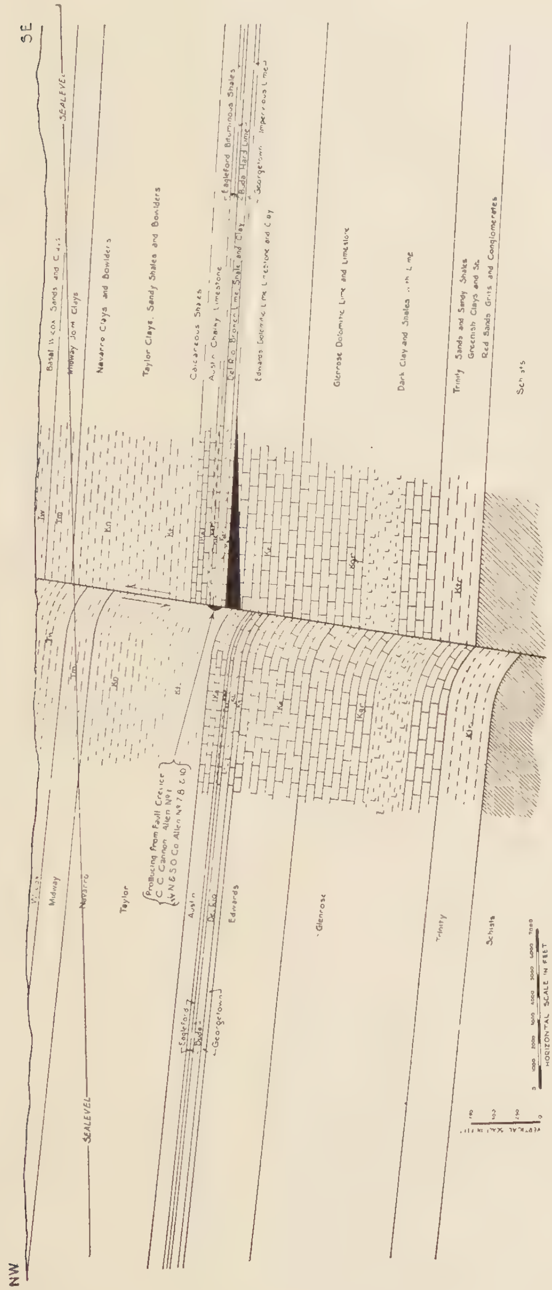

NW
SE
SEALEVEL
Basal Wilcox Sands and Clays
Midway Joint Clays
Navarro Clays and Bowlders
Taylor Clays, Sandy Shales and Bowlders
Calcareous Shales
Austin Chalky Limestone
Del Rio Brown Lime, Shale and Clay
Eagleford Bituminous Shales
Buda Hard Lime
Georgetown Impervious Lime
Edwards Dolomitic Lime Limestone and Clay
Glenrose Dolomitic Lime and Limestone
Dark Clay and Shales with Lime
Trinity Sands and Sandy Shales
Greenish Clays and Ss.
Red Sands Grits and Conglomerates
Schists
Tw
Tm
Kn
Kt
Ka
Ke
Kgr
Ktr
Wilcox
Midway
Navarro
Taylor
Producing from Fault Crevice
C C Cannon Allen No 1
W N & S O Co Allen No 7 8 & 10
Austin
Del Rio
Edwards
Eagleford
Buda
Georgetown
Glenrose
Trinity
Schists
0 1000 2000 3000 4000 5000 6000 7000
HORIZONTAL SCALE IN FEET
VERTICAL SCALE

FIG. 86.—Generalized northwest-southeast cross-section showing stratigraphy and structure of the Luling fault. After Brucks, E. W.: A. A. P. G. Bull., Vol. 9, p. 638, 1925.

The oil was found in porous dolomitic beds in the upper portion of the Edwards limestone. The accumulation of oil is very definitely in keeping with the gravitational arrangement, water under pressure being in contact with the oil all along the southeastern side of the pool. The initial yields of the individual wells vary widely, those of equally favorable structural location seldom having the same initial capacity because of porosity variations.

The shallow subsea depth of the Edwards limestone, 1,590 to 1,720 feet depending upon the location with respect to the fault, would suggest possibilities of other deeper horizons. However, a test well drilled to a depth of 4,790 feet encountered only showings of oil-stained sand in the Trinity and then drilled into a schist. The metamorphic character of the latter precludes any thought of deeper sources of oil than the Lower Cretaceous. Because of the relatively short distance to the basement crystallines, it has been suggested that the fault is a direct vertical uplift resulting from underlying movement. Brucks mentions unusual temperatures encountered in drilling the schist and suggests the existence of an underlying igneous ridge.

The oil of Luling is a typically asphaltic type, quite different from the oils found in the Woodbine in the Mexia district. Luling oil is of 27° Baume gravity, while that of the Mexia area averages above 35°. If of the same origin, that is, probably from the Eagleford shales, the oil must have migrated downward and have been greatly altered. Other suggestions are that the oil was indigenous to the Edwards limestone or that it was derived from formations of considerably greater depth and had moved upward through the fractured fault plane. None of the explanations are wholly satisfactory.

Irvine-Paint Creek Fault.[1]—A zone of faulting and folding of some considerable importance extends across the state of Kentucky in an east-west direction. In the eastern part of the state it is known as the Irvine-Paint Creek-Warfield fault and fold. In the central part of the state it is called the Kentucky River fault and fold; and in the western, referred to as the Rough Creek.

The eastern portion of the zone is held to be directly responsible for the location of a number of the more important pools of the state.

---

[1] Data mainly from:

Shaw, E. W.: The Irvine oil field, Estill County, Ky., U. S. G. S. Bull. No. 661, pp. 141–192, 1918.

St. Clair, Stuart: The Irvine oil district, Kentucky, Min. and For. Resources, Kentucky, ser. V, Vol. 1, pp. 58–76, 1919; and Am. Inst. Min. and Met. Eng. Bull., pp. 1078–1089, July, 1919.

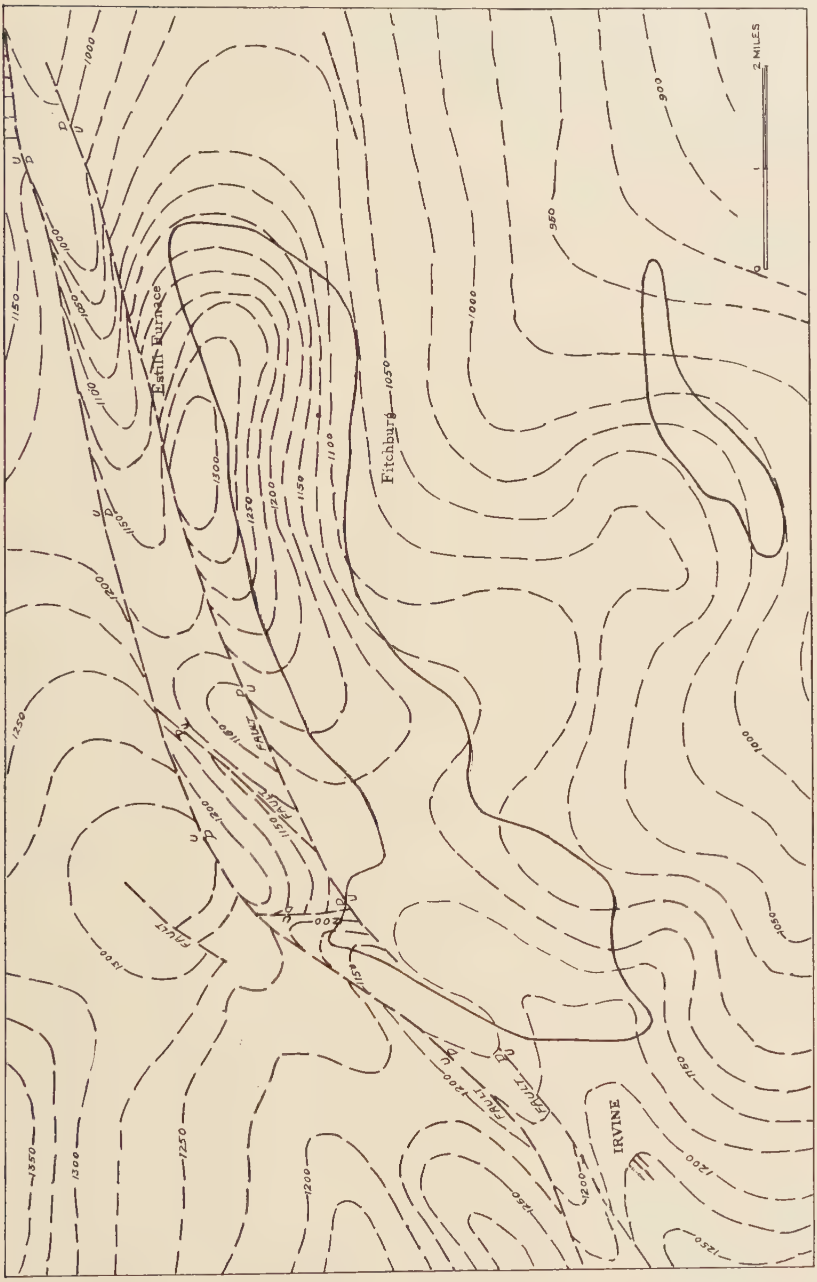


FIG. 87.—Geological sketch map of the Irvine oil pool and vicinity, Kentucky. Solid line shows extent of productive areas. Adapted from Shaw, E. W.: U. S. G. S. Bull. 661, Plate 14, 1918.

The relationship between the location of the oil- and gas-containing areas and the fault line is particularly strong on the western flank of the southwestward trending Appalachian geosyncline. This includes sections between Morgan and Estill Counties. Production has been obtained on the north side of the fault zone away from the basin but is not of importance except in areas more than five miles away from it. On the south side of the fault a number of pools have been developed. Some of these lie close to the fault zone and others a short distance south of it. Those to which distinctive names have been given include Station Camp, Irvine, Big Sinking, Campton, Stillwater, and Cannel City.

The major development of the area began in 1915, but oil had been produced on a small scale for a number of years previous to that. In 1903 the Campton pool in Wolfe County was opened and about 300 wells drilled. The wells were comparatively shallow and easily drilled, but the yields were small and not well sustained. Shortly afterward some shallow drilling was done in the vicinity of Irvine in Estill County, and a small production developed. The Cannel City pool was opened up in 1912; and, while the center of great activity for a time, proved to be short lived.

The slightly deeper wells drilled at Irvine in 1915 proved to be of better average yield and longer life than any of those drilled previously. The productive area was extended to cover a considerable area including such sections as Ravenna, Fitchburg, and Station Camp. The most important extension was made in 1918 when the Big Sinking pool was opened. In 1918 the total production of the several pools was more than two and a half million barrels. As practically none of the wells were more than a thousand feet in depth and most of them only a few hundred feet, the drilling costs were low and development work was easy and rapid.

The productive horizons are porous portions of the Onondagan and Niagaran limestones. They are relatively thin, the average thickness being not over 20 to 25 feet in the best wells. They vary considerably and the yields from the wells have reflected the variations. When opened, the horizons showed only relatively small amounts of gas. The gas pressure was low, but sustained water pressure assisted in the recovery of the oil. Water was found early in the development on the southern edges of the producing belt.

The productive area of the Irvine pool proper seemed to correspond rather closely with the general outline of an anticlinal area immedi-

TABLE 53.—COMBINED SECTION IN ESTILL COUNTY.*

(The column showing depth has been recalculated to conform with other sections.)

	Thickness.	Depth.	Geologic formation.
	Feet.	Feet.	
Heavy sandstone	196	196	Conglomerate measures.
Shales and shaly sandstone	50	246	
Black slate	4	250	
Coal	1	251	
Gray shales	4	255	
Coal	1	256	
Shales	15	271	
Buff earthy limestones	8	279	Chester, 33 feet.
Archimedes limestone	2	281	
Gray limestone	13	294	
Calcareous shales	10	304	
Oolitic limestone	10	314	St. Louis, 150 feet.
Buff limestone	11	325	
Semioolitic limestone	22	347	
Gray limestones	12	359	
Earthy buff limestone	5	364	
Thin gray cherty limestones	24	388	
Massive limestone	22	410	
Blue limestone and shale	38	448	
Earthy yellow limestone	6	454	
Sandstones and shales	490	944	Waverly, 490 feet.
Black shale	125	1,069	Devonian shales, 125 feet.
Estill County oil sand	25	1,094	Corniferous, 25 feet.
Blue and gray shales	145	1,239	Niagara, 150 feet.
Gray lime	5	1,244	
Gray lime	25	1,269	Clinton, 53 feet.
Gray shale	10	1,279	
Gray lime	8	1,287	
Red lime	10	1,297	
Gray lime	17	1,314	Lower Silurian (Ordovician), Hudson and Trenton groups, 1,476 feet.
Brown lime	40	1,354	
Gray lime	839	2,193	
Greenish-white friable shaly sandstone	10	2,203	
Hard fine-grained limestone, dark dove-color, with occasional bands of dark-blue hard limestone	425	2,628	
Hard gray limestone	145	2,773	
White fine-grained sand and lime	15	2,788	Calciferous (St. Peter?).
Bottom of Whiteoak well			

---

* After Shaw, E. W.: U. S. G. S. Bull. 661, p. 154, 1918.

ately south of the fault. The production farther to the south came from terraced areas and sections of purely monoclinal slope. Very few productive wells were found in the fault zone or immediately south of it. In the latter case the absence of oil was probably due to porosity variations as the sections were structurally favorable.

The normal dip in this region is about 35 feet to the mile in a southeast direction. The only strong structural features of the area are the faults and the folds immediately associated with them. The fault zone consists of two main lines of faulting with a general east-west trend and a series of minor transverse faults. The downthrow of the southern fault line is to the north; and that of the northern break, to the south. The result is a downfaulted block varying in width from one-half to two miles and from 25 to 200 feet lower structurally than the beds to the north and south of it. This particular faulted area can be traced definitely for a distance of 20 miles. Its importance in accumulation of oil can hardly be questioned. While not a fault of major proportions, the throw is generally greater than the maximum thickness of the porous portions of the limestones. Because of this it is just as effective a trap as a larger fault would be. The accumulation in the Irvine pool is further assisted by the arching of the beds close to the fault.

Whittier Fault.[1]—Fault-dominated pools productive of more than 100,000,000 barrels of oil are found on the southwest flank of the Whittier fault in the eastern part of the Los Angeles Basin of California.

This fault is considered to be one of the two faults formed by splitting of the northern end of the Elsinore fault. The strike of the other, the Chino fault, is approximately to the northwest, but that of the Whittier is more to the west. In the V-shaped area between the two lie the Puente Hills. Up to the present time the areas north of the Whittier fault have not proved of interest to the oil producer. On the southern side the Whittier and Brea Canyon-Olinda pools have been important sources of oil since 1900.

The Whittier fault is of the thrust fault type, but movements along the fault plane parallel to its strike have evidently been of greater importance than those of vertical extent. The fault plane appears to

---

[1] Data mainly from:

Eldridge, G. H.: The Puente Hills oil district, Southern California, U. S. G. S. Bull. No. 309, pp. 102–137, 1907.

English, Walter A.: Geology and Oil Resources of the Puente Hills Region, Southern California, U. S. G. S. Bull. No. 768, 1926.

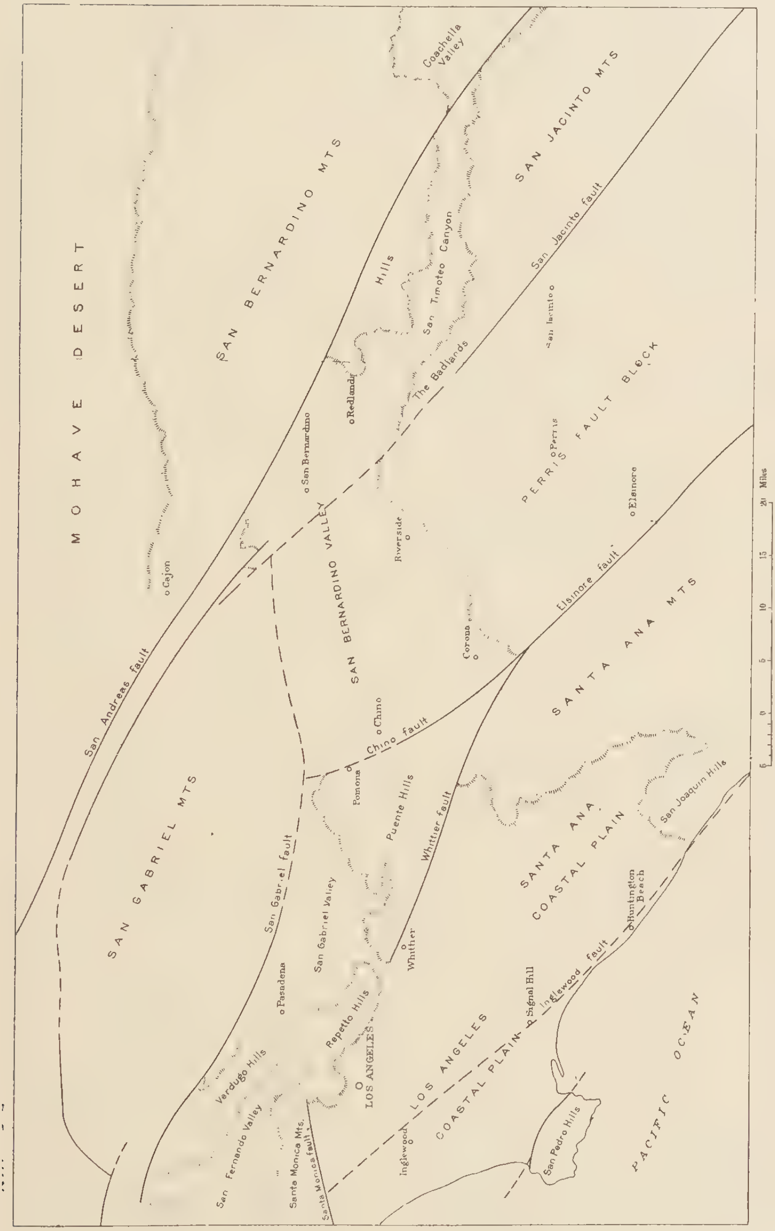


FIG. 88.—Map showing principal structural divisions of Southern California. After English, W. A.: U. S. G. S. Bull. 768, Plate III, 1926.

be nearly vertical. It may be traced on the surface for a distance of more than 30 miles. For a short distance north of the town of Whittier and near the northwestern end of the fault, the downthrow is to the north. Eastward from Whittier almost to the valley of the Santa Ana River, the downthrow is on the south. This is a distance of about 17 miles. The beds south of the fault in this section belong to the Fernando group, while those to the north of the fault are of the underlying Puente formation. Southeast of the Santa Ana River the throw is again reversed. The Cretaceous beds come to the surface on the south side of the fault zone, while the Puente (Tertiary) is exposed on the north. The section of interest to the petroleum geologist is that between Whittier and the Santa Ana River in which the Fernando shows on the surface in contact with an uplifted block of the Puente north of it. The Whittier pool lies to the northern end of this section and the Brea Canyon-Olinda to the southern.

The Whittier Pool.—This area lies directly east of the town of Whittier. It was first developed at the beginning of the present century. It has been added to by the discovery of new horizons and extensions and still remains a pool of some importance. Throughout the productive area the beds dip sharply to the south. Close to the fault the Fernando is almost vertical, but southward from it the angle of dip is usually between 30 and 45 degrees.

The oil is found through a thickness of 3,000 feet. The lowest sands are close to the bottom of the Fernando and may lie in the Puente. Production is considered to have been derived from five different zones. The zones are not distinctly separated, the division being made primarily because of the occurrence of water sands between the oil-yielding beds. The highest zone was of minor importance; the beds there were thin and productive only in a small area. The second zone lies 500 to 600 feet below the top of the first and is close to 300 feet in thickness. The third is 600 to 700 feet deeper and from 100 to 250 feet thick. The top of the fourth is irregular and nearly 1,000 feet below it. The fifth or deepest zone underlies this and is considered to have a thickness of about 1,000 feet. It is productive in the western part of the pool. The depths to individual zones from the surface are extremely irregular because of the steepness of the dip. This is especially true near the faults. Estimates of thickness are subject to considerable revision as the apparent thickness may be several times the actual because of the attitude of the beds. In some cases the oil horizons outcrop in areas close to the points where they are productive. In these the retention of the oil must be considered as due either to lenticularity of individual sand bodies within the zones or to the sealing effects of asphaltic residues.

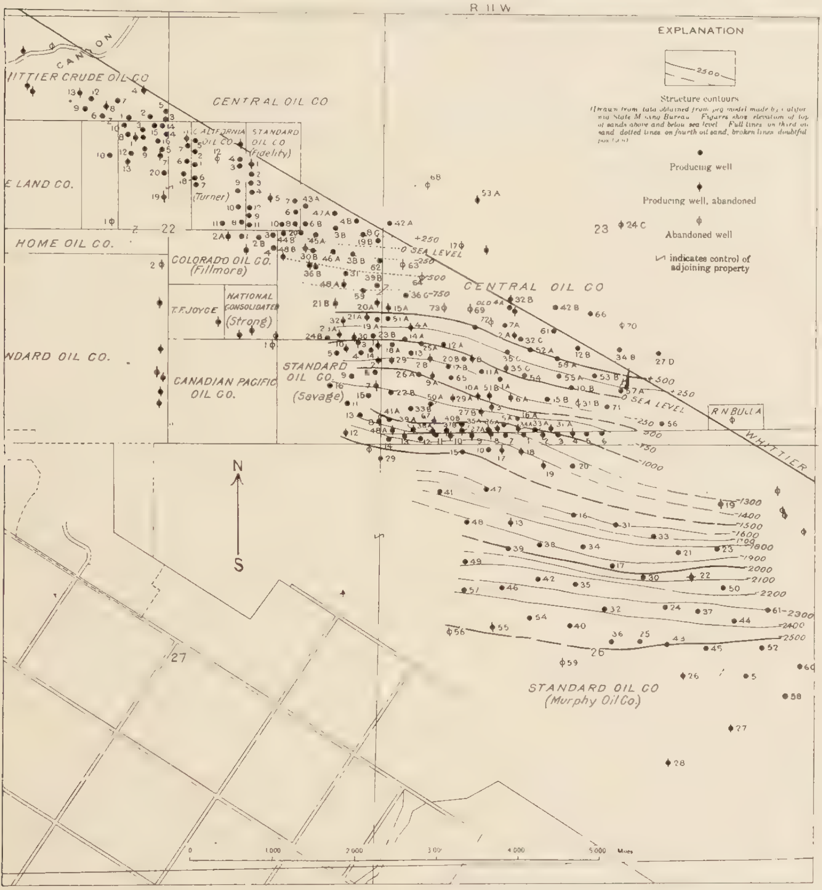

R 11 W
EXPLANATION
2500
Structure contours
(Drawn from data obtained from peg model made by California State Mining Bureau. Figures show elevation of top of sands above and below sea level. Full lines on third oil sand, dotted lines on fourth oil sand, broken lines doubtful position)
● Producing well
♦ Producing well, abandoned
ɸ Abandoned well
indicates control of adjoining property
CANYON
WHITTIER CRUDE OIL CO
CENTRAL OIL CO
CALIFORNIA OIL CO
STANDARD OIL CO (Fidelity)
(Turner)
LAND CO.
HOME OIL CO.
COLORADO OIL CO. (Fillmore)
NATIONAL CONSOLIDATED (Strong)
T.F. JOYCE
STANDARD OIL CO.
CANADIAN PACIFIC OIL CO.
STANDARD OIL CO. (Savage)
CENTRAL OIL CO
+250
0 SEA LEVEL
-250
-500
-750
500
250
0 SEA LEVEL
-250
-500
-750
-1000
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
R N BULLA
WHITTIER
22
23
26
27
N
S
STANDARD OIL CO (Murphy Oil Co.)
0
1000
2000
3000
4000
5000 Miles

FIG. 89.—Map showing geologic structure of part of the Whittier oil pool. After Kew, W. S. W.: U. S. G. S. Bull. 768, Plate VI, 1926.

A few wells have yielded commercial quantities of oil north of the fault line. Their total production would constitute a very small part of the more than 10,000,000 barrels that have been produced from the pool as a whole. Their oil is much lighter than that of the sections to the south of the fault. The average of the main pool is from 14 to 24° Baume. It has been suggested that the light oil has migrated through

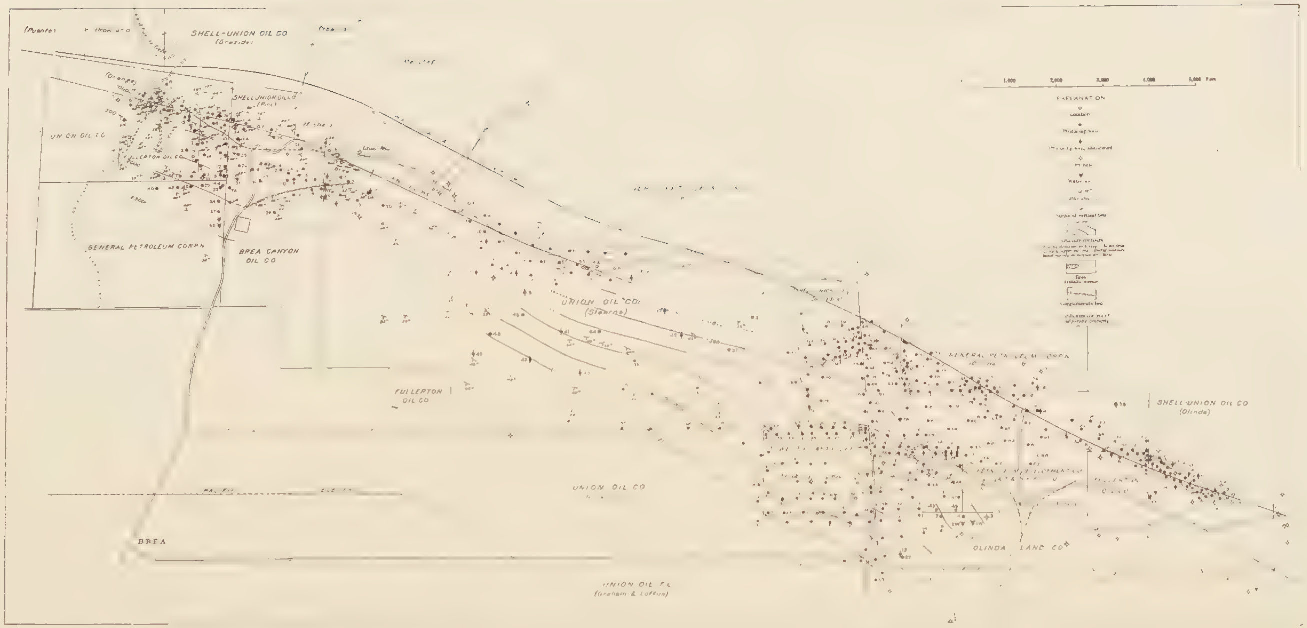


FIG. 90.—Map showing geologic structure of the Brea Canyon-Olinda oil pool, California. Contours on top of upper oil zone. After Kew, W. S. W., and English, W. A.: U. S. G. S. Bull. 768, Plate VIII, 1926.

the fault plane and has been subjected to straining action in that migration. To the south the production is limited by the increasing depth and by the presence of a great number of intermediate water sands, which make operations very difficult. Extensions to the west are possible but are limited at present by the high value of the land in the town of Whittier.

Brea Canyon-Olinda.—The development of this section began in 1900 when discoveries were made simultaneously in two disconnected areas, Brea Canyon and Olinda Canyon. The two areas were later joined by the completion of producing wells in the area between them.

A strong anticlinal fold lies parallel to, and from 1,000 to 1,500 feet south of, the Whittier fault in the Brea Canyon area. The south flank and crest of this fold are highly productive, but the area between the axis and the fault as indicated on the surface is of minor importance. The axis is marked by a line of seepages. East of this area in the Olinda section the effects of the fold become less marked and the productive area comes close to the fault. At the extreme eastern end of the producing area a number of wells lie to the north of the surface trace of the fault. Whether the productive beds reached by these wells are actually north of the fault is not certain. The high quality of the oil, 32 to 35° Baume as against 16 to 24° Baume for the rest of the pool, would suggest this. However, the difficulties of correlation are great, only partial records of the wells being available. The productive area terminates abruptly at the east where a number of dry holes suggest the presence of a transverse fault.

Producing conditions are much the same as those in the Whittier pool. Three zones are recognized. The upper two are definitely placed in the Fernando, but the lowest may be either in that formation or in the underlying Puente. Less trouble has been encountered from water in the upper parts of the structure than at Whittier, and wells of higher average capacity have been secured. The total production has been ten times as great, being more than 100,000,000 barrels to the end of 1926. Yet the area is less than twice that of Whittier and does not total more than 1,000 acres. The productive limits of the pool to the south are defined by the presence of edge water.

Santa Clara Fault.[1]—The Santa Clara or Oak Ridge fault is a

[1] Data mainly from:

Godde, H. A.: Oil Fields of Ventura County, California Oil Fields, Vol. 10, No. 5, Nov., 1924.

Kew, W. S. W.: Geology and Oil Resources of a Part of Los Angeles and Ventura Counties, California, U. S. G. S. Bull. No. 753, 1924.

Taliaferro, N. L., Hudson, F. S., and Craddock, W. N.: The Oil Fields of Ventura County, California, A. A. P. G. Bull., No. 8, pp. 789–829, 1924.

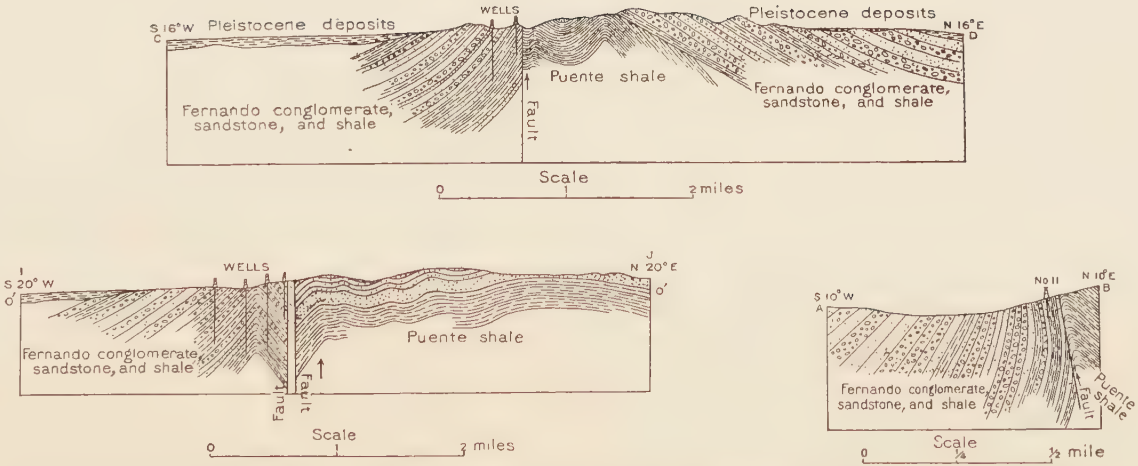


FIG. 91.—Geologic sections across the Whittier fault A B and C D Whittier pool, I-J Olinda area. After Eldridge, George H.: U. S. G. S. Bull. 309, Plate XI, 1907.

thrust fault having a general east-west strike located on the southern edge of the narrow Santa Clara Valley of California. The faulted zone extends east from the vicinity of the town of Santa Paula for a distance of 16 miles. On the north side of the valley at that point, beds of the Fernando group outcrop and dip gently to the south. On the south side are steeply dipping beds of the Middle Sespe formation. The stratigraphic difference between the two series of beds is 8,500 feet. As the distance across the valley at that point is only 8,200 feet, a downward displacement to the north of tremendous size is indicated. The exact position of the fault is hidden by alluvial deposits in the valley but is believed to be along its southern edge.

Hudson reports the finding of upper Middle Sespe beds dipping strongly to the south in the Willard Canyon. This lies on the south or upthrow side of the fault and between it and the crest of the South Mountain dome. From this and from the positions of the beds indicated by study of the logs of wells in the South Mountain pool, he considers that the fault is of the reverse type and has a dip to the south of about 60 degrees. There is also evidence of minor faulting of the same nature parallel to, but south of, the main fault line. The effects of some of these faults have been noted in drilling operations.

This is not the only major fault line in the area but is closely related to others to the north and to the south. South of it is the large Santa Rosa fault. The most important area of faulting lies immediately north of the Santa Clara Valley in the foothills of the Coastal Ranges. This fault zone is known as the San Cayetano fault and has been traced for more than 40 miles. Its thrust is toward the south. Another fault zone, the Santa Susana, extends eastward from a point a short distance south of the eastern end of the Santa Clara. It is closely related to the San Cayetano, having a thrust to the south.

The faulting along the Santa Clara line has apparently resulted from intense thrusting from the south. This caused the development of an inclined asymmetrical and partially overturned fold having its steep side to the north and its axial plane inclined to the south. This fold, if taken alone, has the form of a long anticlinal ridge and has been called the Oak Ridge anticline. The anticline is not uniform but is composed of a number of high spots with intervening saddles. The high spots, called domes though they are usually considerably elongated, have proved of especial interest to the geologist. They are from west to east: South Mountain, Barsdale, Montebello or Shiells Canyon, Wiley Canyon, and Torrey Canyon. No oil has been taken

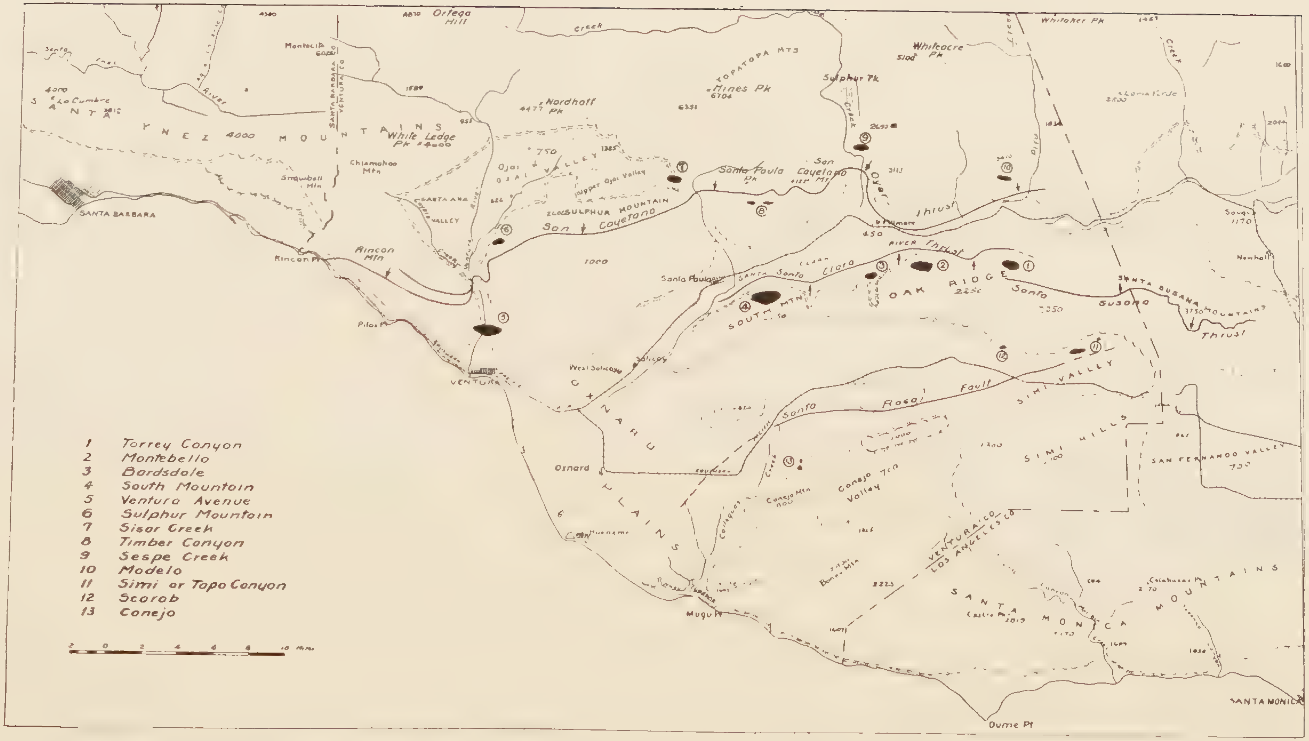


FIG. 92.—Oil pools in Ventura County, California. Map showing relations of pools to major faults. After Taliaferro, N. L., Hudson, F. S., and Craddock, W. N.: A. A. P. G. Bull., Vol. 8, p. 789, 1924.

from Wiley Canyon. Torrey Canyon began to produce from shallow depths as early as 1889. It was still producing 250 barrels a day in 1924. The Barsdale pool began to produce in 1896 and was still producing 75 barrels daily in 1924. The Shiells Canyon pool was not opened until 1911 but has been an important producer since then and was still able to produce 1,000 barrels daily in 1924. The South Mountain pool was the last to be discovered, the first well there being drilled in 1915. The pool produced more than 6,000,000 barrels of oil to the end of 1923 and was then capable of yielding 4,000 barrels a day.

While north of the Santa Clara fault trace beds of the Fernando and Monterey formations are known, they have been eroded from the domed areas in which the oil is found south of the fault. In these the upper part of the Sespe usually shows at the surface while the drill penetrates the middle and lower portions of the formation. The drill has not passed through the Sespe into the underlying Eocene in any of the wells drilled up to the present. Intrusive dacites have been noted at various points in the area but have not been encountered in the producing sections.

The productive beds are found in the middle of the Sespe, except where that has been removed as in the South Mountain dome, and in the beds of the lower part of the Sespe. The beds of this formation are of the typical ''red-bed'' type and are believed to be of non-marine origin. The Sespe cannot be considered as the original source of the oil it now contains. Underlying Eocene beds are considered by some to have been the source of the oil. Seepages from beds of this age have been noted in the mountains north of the San Cayetano fault. The Monterey is also a possible source of the oil as these beds lie below the Sespe on the north side of the fault plane. This might assist materially in the migration of the oil from the shales into the Sespe.

South Mountain.—While the several domes are not exactly identical, their general forms are much the same. Their relations to the Santa Clara fault line are also similar. Because of this only the recently developed South Mountain dome will be described. The form of this pool is that of an elongated east-west trending dome. The dips to the east and west of the center are gentle. On the south side the dip increases gradually to 60 degrees. On the north flank the beds dip steeply, the rate of dip increasing rapidly until the beds overturn at a distance of 3,000 feet of the axis. The axial plane is

Table 54.—Formations Exposed in a Part of Los Angeles and Ventura Counties, California.*

System.	Series.	Generalized section.	Thickness (feet)	Character.
Quaternary.	Recent.	Alluvium.		Sand, gravel, and silt in valley bottoms and along streams.
	Pleistocene.	Terrace deposits.	250±	Gravel and sand, partly consolidated, forming terraces, now dissected.
Tertiary.	Pliocene.	Fernando group. Saugus formation.	2,000±	Conglomerate and sandstone, with some shale; mainly of terrestrial origin, but with marine strata in western part.
		Pico formation (restricted).	4,000±	Fine-grained gray sandstone, interbedded with coarse sandstone and conglomerate. Marine in origin. Along south side of Fernando Valley and westward to Las Virgenes Canyon the formation consists of laminated gray sandy shale and fine-grained sandstone with zones or lenses of white diatomaceous soft shale; upper strata largely medium-grained soft sandstone with some conglomerate.
	Miocene.	Modelo formation.	9,000±	Primarily clay, diatomaceous shale, and fine-grained laminated sandstone and cherty beds; contains two or three large lenses of coarse brown and tan sandstone varying in thickness up to 4,000 feet; marine.
		Mint Canyon formation.	4,000±	Nonmarine conglomerate, sandstone, and clay, predominantly red in lower part, light gray in upper part; vertebrate fossils indicate an upper Miocene age.
		Topanga formation.	6,000±	Mainly brown, tan, and gray coarse sandstone and conglomerate with prominent zone of medium-grained greenish-brown fossiliferous sandstone containing fauna probably equivalent in age to "Temblor formation" in San Joaquin Valley (*Turritella ocoyana* fauna). Intruded by basic volcanic rock.
		Vaqueros formation.	100 to 1,800±	On Little Sespe Creek and Oak Ridge, mainly gray to buff sandy shale with limy beds and concretions. In Simi Valley, brown conglomerate, coarse and fine sandstone. Marine.
	Oligocene (?).	Sespe formation.	3,500 to 4,000±	Nonmarine red, brown, and yellow conglomerate and sandstone with interbedded shale.
	Eocene.	Tejon formation.	2,000±	In Simi Valley, brown medium to coarse sandstone with interbedded conglomerate. At Sespe Creek, hard greenish-brown sandstone and shale; at top, 500 feet of light-gray sandstone with some shale. Marine.
		Meganos formation.	2,000 to 3,500±	Brown to rusty-colored conglomerate, brown and gray sandstone, and gray shale with calcareous concretions. Marine.
		Martinez formation.	1,500 to 3,500±	Massive basal conglomerate overlain by brown and gray shale and sandstone. Marine.
Cretaceous.	Upper Cretaceous.	Chico formation.	5,000±	Massive brown sandstone with thin beds of greenish-brown and gray shale. 500 feet of calcareous sandstone and shale below massive sandstone contains Upper Cretaceous fossils.
Jurassic (?).	(?)	Intrusive granite.		
Pre-Jurassic		Metamorphic rocks		Micaceous schist and quartzite intruded by granite.

* After Kew, W. S. W.: U. S. G. S. Bull. p. 8, 1924.

naturally inclined to the south bringing the surface axis of the fold a considerable distance to the north of the axis in the oil horizons.

The zonal arrangement of the productive sands is similar to that found in other pools in southern California. They are all in the Lower Sespe. The shallow horizons are small and contain some gas. The deeper horizons are more extensive, and the yields per well are larger. The depth of the wells varies from 1,900 to 4,750 feet, but the average is about 3,300. The wells produce oil of 27° Baume gravity. Edge and intermediate waters have been encountered, but water problems have not been serious because of the orderly development of the pool.

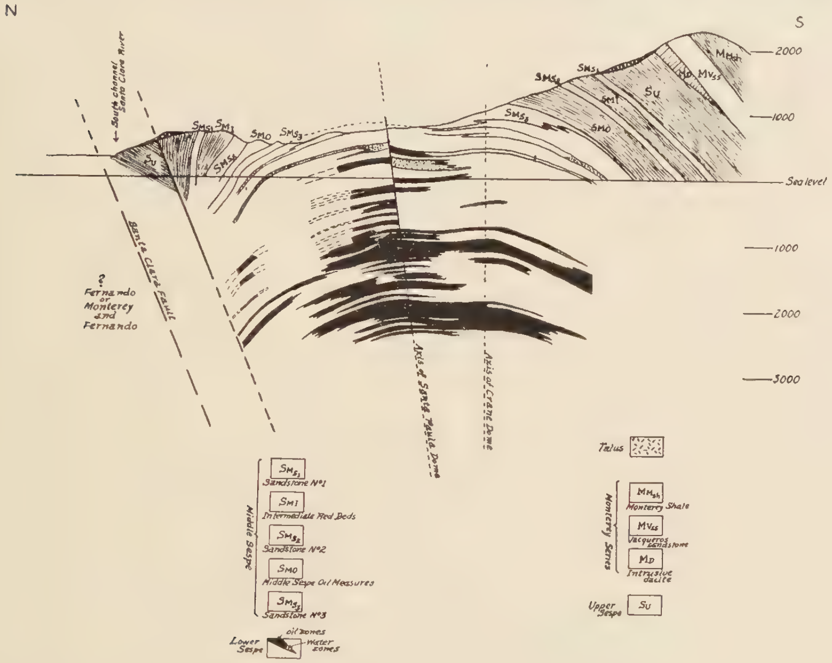


Fig. 93.—Structural section across the South Mountain oil pool, California. After Hudson, F. S.: A. A. P. G. Bull., Vol. 8, p. 818, 1924.

Overthrust Faults, McKittrick, California.[1]—All of the faults discussed up to the present have had relatively high angles of dip. This is probably true of the great majority of the faults found in oil-producing areas. Closely related to the Whittier fault is the Los Angeles fault.[1] While distinctly a thrust fault, it is also of high angle. Like the Whittier fault its southern side is the center of substantial oil production. Faults of much lower angle are found in the general vicinity of the Santa Clara fault, but they are not productive of oil.

---

[1] Data mainly from:

Arnold, Ralph, and Johnson, H. R.: Preliminary Report on the McKittrick-Sunset Oil Region, U. S. G. S. Bull., Vol. 406, 1910.

English, W. A.: Some Notes on the Geology of the South San Joaquin Valley, California, A. A. P. G. Bull., Vol. 11, pp. 617–620, 1927.

In the San Joaquin Valley commercial production has been obtained at one place from strata that have been subjected to low-angle faulting of considerable intensity. The point is in the northern portion of the McKittrick district. The section lies on the east slope of the Temblor Range. The whole area has been subjected to folding and thrust faulting by compression from the west. This has resulted in a series of overturned and complex folds. These are productive in

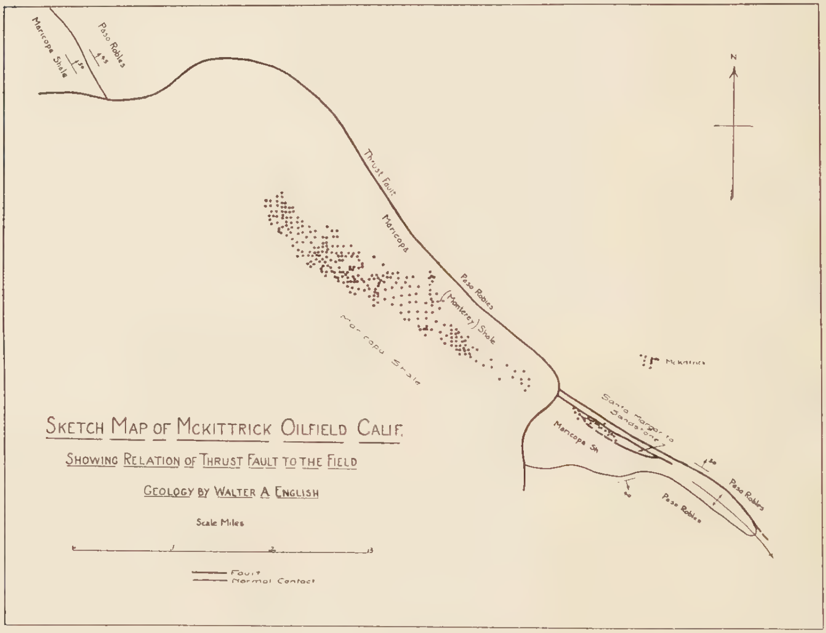


FIG. 94.—Sketch map of the McKittrick oil pool, California. After English, Walter A.: A. A. P. G., Vol. 11, p. 618, 1927.

---

[1] Eldridge, G. H., and Arnold, Ralph: The Santa Clara, Puente Hills, and Los Angeles Oil Districts, California, U. S. G. S. Bull. No. 309, pp. 135–198, 1907.

the southern portion of the McKittrick district, where their outlines show in the outcropping strata. In the northern portion, however, the structure of the productive beds is concealed by the presence of older beds, which have been thrust over them from the west.

The surface strata in the area covered by the overthrust consist of a series of closely compressed and overturned folds. The records of the wells drilled in the area indicate the existence of a low northeastward-dipping monocline with a very slight reverse dip at the depths where the oil was obtained. The gravel and conglomeratic sand horizon, which contains the oil, has been identified as the basal portion of the McKittrick formation. Below it the Monterey and the Santa Margarita shales were encountered in their normal position. Above the oil-yielding zone a similar succession was identified. A limited amount of gravel and conglomeratic material typical of the bottom of the McKittrick was found in synclinal portions of the beds showing at the surface. Below these and also occupying the area of the overthrust are beds of the Monterey and the Santa Margarita. Thus the McKittrick beds, which normally in this area are found to rest unconformably upon the shales of the Monterey and the Santa Margarita, are covered by those shales.

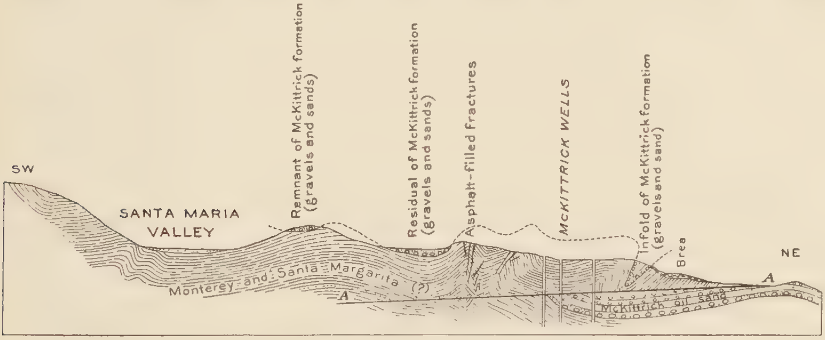

SW
SANTA MARIA VALLEY
Remnant of McKittrick formation (gravels and sands)
Residual of McKittrick formation (gravels and sands)
Asphalt-filled fractures
MCKITTRICK WELLS
Infold of McKittrick formation (gravels and sand)
Brea
NE
Monterey and Santa Margarita (?)
A
A
McKittrick oil sand

FIG. 95.—Cross-section of part of the McKittrick district, California. After Arnold, R., and Johnson, H. R.: U. S. G. S. Bull. 406, p. 97, 1910.

The distance of the thrust appears to have been about a mile along a front of about five miles. At the ends of the zone affected two transverse faults appear to have been developed. These may have tended to prevent lateral migration of the oil. The producing oil zone is about four miles long and from a few hundred feet to a half a mile in width. At the southern end the older rocks do not appear above the oil-containing ones, but the producing belt continues.

Very little is known of the producing conditions beneath the thrust plane. The continuance of the producing belt to the southeast of the faulted area and the absence of oil in the northern portion, where the faulting is most severe, suggest that the accumulation at the base of the McKittrick is due more to structure within the beds below the fault plane than to the contact between porous McKittrick beds and the dense shales above the fault plane.

The oil in the overthrust area averages 15 to 16° Baume. This is much the same as that in other portions of the district. Production of individual wells has been as high as 300 barrels a day. No water has been found in association with the oil in the fault area, but above the main producing zones tar sands and gas such as are found in adjacent unfaulted areas are present.

Summary.—In areas such as the United States where the great majority of the producing pools are divided among two or more owners even the minor fault is of great importance. Yet as a general rule faulting is seldom the cause of the accumulation in the structure as a whole. Where faulting is the major factor in causing accumulation, the faults are found to be of great length and persistence. They are invariably associated with movements in the underlying shear zones and not to be considered as surface phenomena. Because of this the effects of the fault are likely to be traced over a number of miles. Production can hardly be expected to develop along the full length of the faulted zone, but its occurrence is to be expected at points where arching of the beds forms especially suitable areas for accumulation. The discovery of production along a fault plane, which careful study proves to have been the dominating cause of the accumulation, should warrant the expectation of the finding of other productive areas under similar conditions nearby.

CHAPTER XIV.

ACCUMULATIONS CONTROLLED BY POROSITY VARIATIONS.

While variations in the porosities of sandstones and porous limestones are recognized as of major importance in determining the manner of concentration of oil and gas, they are seldom considered as the sole agencies causing this accumulation. Changes in porosity and the lenticular character of productive horizons enter into the calculations of the geologist on such strongly developed anticlinal folds as the La Salle anticline of Illinois and Indiana and the Salt Creek structure of Wyoming. Yet until recently many geologists failed to recognize that these agencies could be even more effective in limiting the occurrence in areas of less pronounced folding.

The effects of changes in porosity of oil-containing horizons are noticed in beds of all ages. They appear to be of less importance in Tertiary and Cretaceous beds than in those of greater age. This may be partly explained by the fact that most of the beds of these ages have not been subjected to as much compacting and cementing as those of the earlier periods. In addition Tertiary and Cretaceous producing areas on the whole are characterized by much more pronounced folding and faulting than appears in the Paleozoic areas which yield oil and gas in commercial quantities. The general absence of oil and gas in the sharply-folded and faulted Early Mesozoic and Paleozoic sediments is considered as an indication of the destruction or escape of these substances in these areas. The present lack of production in areas of slightly-folded Tertiary sediments may reflect the absence of oil in those sections. They have been tested very little by drilling. It is entirely possible that the drill may demonstrate in the future that accumulation has occurred in terraced and lenticular areas of this age just as it has in those of earlier ages.

The causes of differences in the porosities in the various types of rocks found in oil-containing areas were discussed in Chapter VII. Differences in the degree of porosity in any given horizon or group of strata must be considered as due to differences in the application of these causal factors. Probably the most common cause of variations in the porosity of associated sediments is difference in the nature of the sediments laid down in adjacent areas. This usually means differences resulting from the deposition of sands as against clays and silts.

In practically all cases the agency of deposition is water. This may be the water of rivers, lakes, epeiric seas, or of the ocean itself. The form of the deposit laid down varies with the conditions at the place of deposition. Many sand deposits are continuous over large areas. However, even the largest must terminate, either in an area of no deposition such as an elevated land surface, or by transition into deposits of another and usually unlike type. Sand bodies deposited by strong ocean currents or at the mouths of delta-forming rivers are likely to vary considerably in thickness within short distances. The horizontal extent of such bodies is seldom large. Sands deposited in the beds and along the banks of streams and rivers will be even more irregular in outline.

Sand is the typical shallow-water deposit. As such, it is commonly laid down upon surfaces which had been subject to erosion only a short time previous. The uneven character of their surfaces is reflected in the irregularities in the form of the sediments deposited upon them. Where the agencies of weathering had functioned more rapidly than those of removal, the sediments were frequently laid down upon a partly weathered and highly porous base.

In a number of instances the crustal action that converted an area of erosion into one of deposition was both rapid and intense, massive limestones and thick beds of shale being deposited immediately on top of the eroded surfaces. The only material which could be conceived of as functioning as a container rock at a later date would be that contained in the erosion zone itself. While such zones are usually thin, they may form ideal containers because of high porosity. Because of their unconformable contact with the strata deposited above and around them, they commonly have unusual drainage range.

The solubility of limestones makes it possible to extend the vertical range of the erosion zone considerably in areas of such rocks. Waters circulating through joint and bedding planes and similar openings may produce a zone of abnormal porosity of substantial depth. The areas so affected will not be continuous but will vary with the topography and with the distribution of the original openings through which the water circulation took place.

Similarly the introduction of cement is seldom regular but is determined by the manner of the circulation of the waters containing the cementing materials in solution. The movements of such waters through bodies of sandy and bouldery nature either before or after their burial are extremely irregular and respond to the slightest variations in topographic or structural conditions and in the characteristics of the media through which they move. Differential cementing is probably responsible for more sudden and erratic variations in the porosities of productng horizons than any other single condition. With such variations come marked differences in the behavior of wells, as for instance a dry hole in the center of a group of substantial producers.

Until recently the study of variations in porosity received only minor consideration. The value of a test location was based almost entirely upon its structural position. If it was not located upon a structural ''high,'' it was considered to have practically no value as a test. Yet, many producing wells not located upon such points were found. In some cases the structurally favorable locations were the dry ones, and the productive areas were found to correspond with the synclinal and therefore undesirable sections. One of the greatest of the early discoveries in Oklahoma, the Glenn pool, is located on a westward sloping monocline. In another in the same state—the Burbank pool—the areas of maximum production are distant from those which would be chosen upon structural considerations alone.

One of the most serious drawbacks to the study of such conditions is the difficulty of obtaining the necessary information. The data needed by the geologist are not available until the drilling wells have penetrated the oil horizons. The taking and examination of drill cuttings and cores is slow. The speed with which offset drilling campaigns must be carried out makes it difficult to gather the data and draw the conclusions in time to apply them. Moreover, the data gathered in one drilling area are seldom of more than the most general value in work in adjacent areas. The development of petroleum production engineering and especially the increased use of special recovery methods tends to increase the value of such studies. It is hoped that through this it may be possible to gather more information upon which to base definite conclusions.

Lensing Sands.—In nearly every one of the major producing areas of Paleozoic age, there are wells that produce from sands which are designated as ''strays.'' Production in such sands is usually limited to a very few wells and apparently bears little or no relation to the structure that determines the accumulation in the major horizons. Such bodies are the bane of every geologist who works with them. Their extent is uncertain; and the behavior of wells drilled to them, erratic. They represent in most cases the deposition of sands in areas covering a few acres. Occasionally they cover areas of two or three square miles. As a general rule, where sand bodies are deposited over areas exceeding this, accumulation follows lines laid down by structural conditions. In some cases the sand body has not been folded sufficiently to form the structures in which accumulation might take place. In such instances migration of gas and of oil may continue for long distances up the dip of a gently sloping horizon until it is ended by reaching the end of that horizon. This has apparently occurred in a large number of cases in the sand horizons contained in the Devonian shales of the Appalachian Field and in the Cherokee shales of northeastern Oklahoma. One of the largest of the horizons in which accumulation is determined primarily by the lensing-out of the sand body is the Clinton sand of Ohio.

Clinton Sand, Ohio.[1]—The Clinton sand is productive over a belt extending through central Ohio from the shores of Lake Erie southward almost to the Ohio River. The first well completed was drilled in 1887. It was a gas well. Oil was discovered in 1899 in the horizon; but, while a substantial amount of oil has been produced since that time, the horizon is known primarily as a gas source.

The Clinton sand is found in the Clinton formation of the Silurian. The name "Clinton" as used here is not considered to be entirely correct, the formation being more properly correlated with the Medina formation of the same period. However, the term Clinton has been in general use for so many years and has been so widely accepted that the possibility of changing the usage is not great. The formation is made up largely of shale in central Ohio. It is calcareous in many parts and occasionally contains beds of hard limestone.

In most places it contains one or more sand layers. One of these lying 35 to 50 feet above the top of what is known as the Medina is the Clinton sand of the drillers. It is a gray to red quartz sandstone. It

---

[1] Data on the Clinton Sand mainly from:

Bonine, C. A.: Anticlines in the "Clinton" Sand near Wooster, Wayne County, Ohio, U. S. G. S. Bull. 621, pp. 87–108, 1916.

Bownocker, J. A.: The Clinton Sand as a Source of Oil in Ohio, Econ. Geol., Vol. 6, pp. 37–50, 1911.

Rogers, G. Sherburne: The Cleveland Gas Field, U. S. G. S. Bull. 661-A, pp. 1–68, 1917.

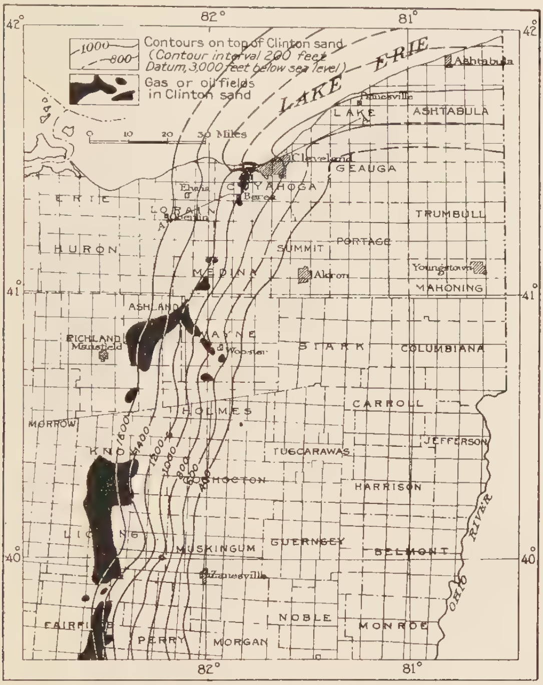


Fig. 96.—General structure map of the Clinton sand in North Eastern Ohio. After Rogers, G. S.: U. S. G. S. Bull. 661, p. 28, 1918.

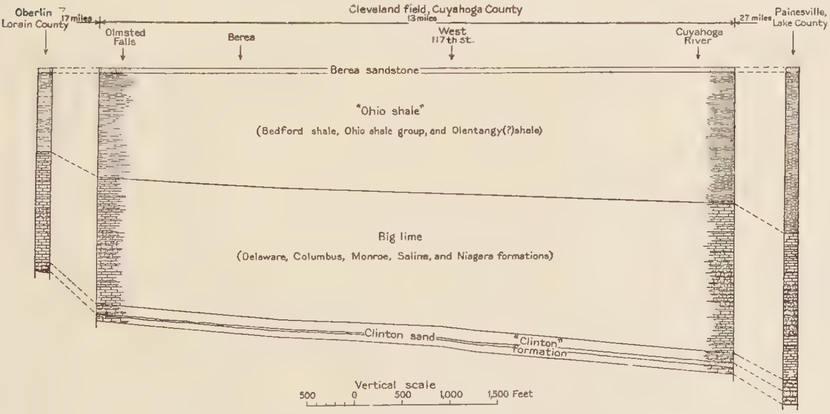


Fig. 97.—Geologic section from Oberlin through Cleveland to Painesville, Ohio, showing eastward thickening of formations below the Berea sandstone. After Rogers, G. S.: U. S. G. S. Bull. 661, p. 13, 1918.

TABLE 55.—GENERALIZED SECTION OF ROCKS IN THE CLEVELAND GAS DISTRICT, ON THE EASTERN FLANK OF THE CINCINNATI ARCH.*

System.	Group or formation.		Thickness in feet.	Character.	Driller's description.
Quaternary (Pleistocene series).	Glacial drift.		10–400	Boulders, pebbles, sand, and clay.	Drift.
Carboniferous (Mississippian series).	Berea sandstone.		40–150	Medium to coarse grained white buff, or brown sandstone.	Berea grit.
Devonian or Carboniferous.	Bedford shale.		60–80	Bluish-gray to reddish shale, with some thin layers of limestone.	Ohio shale, 1,100–1,400 feet.
Devonian.	Ohio shale group.	Cleveland shale.	50–120	Massive hard black bituminous shale with a few bluish layers in lower portion.	
		Chagrin shale.	850–1,200	Soft bluish-gray clay shale, with some concretionary layers.	
		Huron shale.		Black and bluish shale in upper and lower portions, with a band, of gray shale near middle.	
	Olentangy (?) shale.		80	Gray calcareous shale.	
	Delaware limestone.		500–700	Blue and gray limestone, becoming dolomitic in lower part. Contains a 30 to 50 foot bed of white quartz sandstone 350 to 450 feet below top.	Big lime [includes Newburg sand and some "stray" sands in lower 300 feet], 1,425–1,825 feet.
	Columbus limestone.				
Unconformity— Silurian.	Monroe formation.				
	Salina formation.		400–600	Shale, dolomite, anhydrite or gypsum, and rock salt.	
	Niagara limestone.		400–600	Dolomite and limestone.	
	"Clinton" formation.		150–250	Calcareous shale and thin-bedded limestone, with sandstone layer in lower part.	[Includes, Little lime], 75–150 feet.
					Clinton sand, 0–60 feet.
					25–75 feet.
	"Medina" shale.		300–400	Red clay shale with thin layers of sandstone.	Medina red rock.
Ordovician.	Shale and limestone of Cincinnatian age.		1,100–1,250	Dark shale with thin layers of limestone, especially in upper part.	Slate and shells.
	Trenton (?) limestone.		(?)	Limestone.	Trenton lime.

* After Rogers, G. Sherburne: U. S. G. S. Bull. No. 661, p. 5, 1918.

sometimes contains lenses of shaly material or is divided by hard impervious layers. The Clinton formation itself has a thickness of 150 to 200 feet at its outcrops in west-central Ohio. The Clinton sand, however, does not outcrop but feathers out along a line running north and south a little to the west of Cleveland. In the producing area the maximum thickness of the sand is usually 60 feet, but to the east it sometimes reaches a thickness of 100 feet.

The dip of the rocks toward the east is regular throughout the whole of the producing belt, averaging about 50 feet to the mile. Minor folds in the formation serve to determine the areas of maximum accumulation and production, but the gas-containing area corresponds closely to the western edge of the sand body and to the regional structure of the formation rather than to local conditions. Several exceptions to this have been noted. One is found at Wooster, in Wayne County. Here a strong plunging anticline has extended the productive area a considerable distance to the east. In general, however, it can be said that wherever unusual conditions are noted, they may be traced to thinning or thickening of the sand body or to occurrence of unusually tight or cement-filled parts or abnormally high porosities of local extent. There is very little water present in the Clinton sand. This is considered to be responsible for the low gas pressure and the wide distribution of the gas and oil contained in the horizon.

Horizons of Varying Porosity.—Oil and gas are not infrequently obtained from areas of monoclinal slope that are many miles down the dip from the points where the producing horizon is known to feather out. They are separated from those points by sections in which the horizon is either water-bearing or apparently dry. In some instances the producing horizon actually outcrops.

One explanation of the occurrence of such conditions is the lack of continuity of individual sand bodies despite the continuity of the horizon as a whole. This condition apparently holds in a number of places in thick sandy horizons such as the Bartlesville or Glenn sand of Oklahoma and the Hundred Foot sand of Pennsylvania. Somewhat similar conditions apparently have influenced the distribution from the so-called ''breaks'' in the Marble Falls limestone of northern Texas and the Mississippi lime of northern Oklahoma and southern Kansas. These breaks consist of thin sands, sandy limestones, or simply porous portions in otherwise dense limestones. Breaks are commonly found at similar stratigraphic levels within these formations in adjacent producing areas. However, they cannot be considered as continuous bodies, inasmuch as intervening wells frequently fail to find the slightest trace of the break. An example illustrating such conditions and their importance in determining production is given in Chapter XVII, page 414, where the producing area at Ranger in northern Texas is discussed.

In other cases, however, the drill shows the main body of the sand to be definitely continuous. Yet wells having ideal structural locations fail to show even a trace of oil. In most cases such wells are free of water also. The explanation is necessarily one of differences within the sand body itself. This may be differences in the size or assortment of the grains or irregularities in the degree of its cementing.

It is difficult to explain such variations by recourse to any single causal factor; in most cases, it would appear that several have contributed materially to the result.

Glenn Pool, Oklahoma.[1]—The discovery well in the Glenn pool was drilled in 1906. Two years later the annual production exceeded twenty million barrels. Yet the area was not one of sensational wells. A number yielded more than a thousand barrels daily, but the average well was not comparable with the gusher wells completed in recent years in the deep horizons found in pools to the southwest and west of the area. Glenn pool proper occupies an area of about fifteen square miles lying between the towns of Kiefer and Glennpool; but if the various extensions be included, the area is considerably greater. The chief productive horizon, the Glenn sand, was found at a depth of about 1,500 feet. Because of this and the absence of difficulties in drilling, the area developed rapidly.

The dip of the Pennsylvanian surface beds in the vicinity of the producing belt is about fifty feet to the mile to the west. The absence of continuous outcrops makes the determination of minor flexures in surface beds uncertain. A contour map drawn from surface data by C. D. Smith shows the normal dip in these beds to be interrupted only by the presence of a series of undulating incipient folds with axes pointing toward the west. They are not strong enough to produce closures. Glenn pool proper corresponds roughly in position with the outline of one of these, but a similar slightly elevated area immediately to the north is marked by dry holes.

[1] Data on Glenn pool mainly from:

Smith, Carl D.: The Glenn Oil and Gas Pool, and Vicinity, Oklahoma, U. S. G. S. Bull. 541, pp. 34–48, 1914.

Wilson, W. B.: Geology of Glenn Pool of Oklahoma, A. A. P. G. Bull., Vol. 11, pp. 1055–1066, 1927.

While there is no definite unconformity between the surface beds and the producing sands found in the lower part of the Cherokee shales, their structure is quite different. The Cherokee formation as

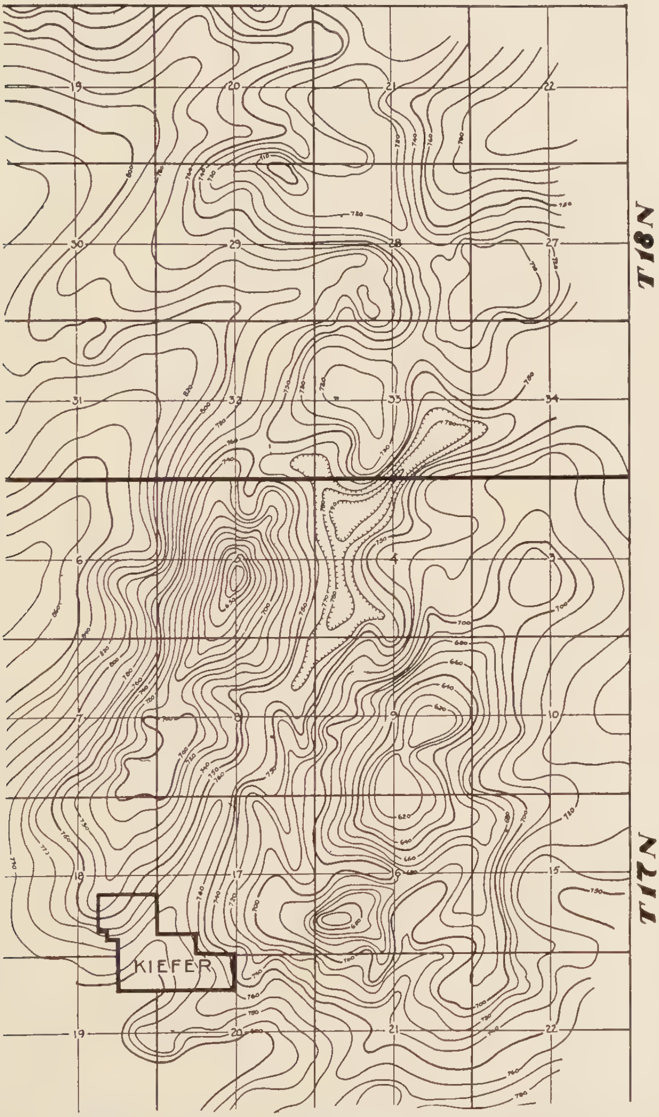


FIG. 98.—Subsurface map of Glenn Pool, Oklahoma, contoured on Bartlesville or Glenn Sand. Contours in depths below sea level. After Wilson, W. B.: A. A. P. G. Bull., Vol. 11, p. 1059, 1927.

a whole thickens materially toward the south, thus tending to accentuate southwestern dips and to decrease the slight northwestern slopes. In addition local folds having definite closures appear when the top of the Glenn or Bartlesville sand near the base of the Cherokee formation is contoured. In part these closures are due to irregularities in the thickness of the Glenn sand and to the differences in the position of the oil within the sand body. However, the more definite closures reflect the position of true folds which have been contoured in the Mounds or Wilcox sand. This is found in Glenn pool at a depth of about 300 feet below the base of the Cherokee formation, the two horizons being separated by the Mississippi lime and the Chattanooga black shale.

The outstanding productive horizon is the Glenn or Bartlesville. Substantial amounts of oil have also been secured from the Red Fork, Tanaha, Dutcher, and Wilcox sands. Several lenticular sands of limited horizontal extent have yielded oil in the southern part of the area. The Wilcox sand is apparently continuous over the whole area. The low quality of the oil found in it here in contrast with the high quality of oil normally contained in the horizon is indicative of the existence of artesian water circulation in this horizon at some time in the past. Wilcox sand production is limited to small areas having definite anticlinal form.

The Tanaha and Dutcher sands lie immediately below the Bartlesville; the Red Fork is a short distance above it. All are in the lower half of the Cherokee shales. The three less important sands are considered as fairly continuous. However, all are relatively thin and appear to be subject to rapid change in both thickness and porosity. Production from them is very irregular in distribution. The Bartlesville or Glenn sand reaches a thickness of more than a hundred feet through much of the producing area. Not all of this thickness is productive, however. Even in the most prolific sections the horizon contains definite breaks of shaly matter or tightly-cemented fine sand. These become more pronounced toward the north and east, the sand rapidly changing into shale. It is to be regretted that the early development of the area militated against the keeping of complete well logs. All that is available in most cases are the sand records. Even these, when no oil was secured, were frequently incomplete. The isopach map of the Bartlesville sand constructed by W. B. Wilson shows a definite decrease in the thickness of the Bartlesville sand to the east of the productive area. The absence of production immediately north and northeast of the town of Glennpool in a section where the thickness of sand reported by drillers is from twenty-five to seventy-five feet indicates that the eastern limit of production is determined as much by the increase in cement content or decrease in size of sand grains as it is by thinning out of the sand.

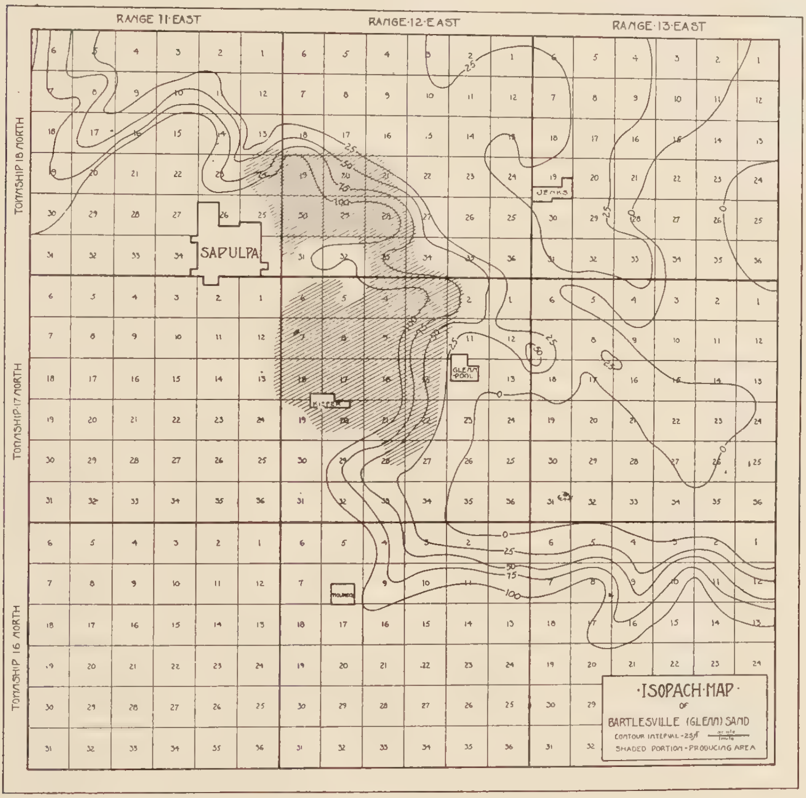


FIG. 99.—Isopach map of Bartlesville sand, Glenn Pool, Oklahoma. After Wilson, W. B.: A. A. P. G. Bull., Vol. 11, p. 1064, 1927.

While the northern and eastern edges of the producing belt are marked by wells which are really dry, those on the western and southern edges find the Bartlesville saturated with salt water. There is no reason to doubt that the migration of the oil is from the south and west and that the trap is due solely to changes in the character of the Bartlesville horizon. The local folds in the Bartlesville do not appear to have been of more than minor importance in the accumulation of oil in this horizon.

Burbank Pool, Oklahoma.[1] - The Burbank pool was discovered in 1920. In May a well was completed in the S.E. quarter of Sec. 36, T. 27 N., R. 5 E.; and in September another, some distance away, in the N.E. quarter of Sec. 9, T. 26 N., R. 6 E. Both of these wells were located in areas in which the surface rocks indicated the existence of favorable structural conditions. Much of the intervening and adjacent areas were considered as of little value at that time because of the lack of definitely favorable structural conditions. Minor synclines are found adjacent to the definitely domed sections, but a general westward monoclinal dip predominates in most of the area. As development proceeded, it was found that the oil was not limited to the comparatively small domed areas but spread out between them and extended northward and eastward for a considerable distance through areas of synclinal or monoclinal character. A number of leases were purchased at auction by the larger producing companies at the rate of more than $5,000 an acre despite the absence of indications of distinctly favorable structural conditions. By the end of 1923, 1,110 producing wells had been completed on 120 quarter sections and 61,923,485 barrels of oil had been produced. Further extensions and the sustained production of the wells made it possible to more than double that figure before the end of 1926.

The Burbank sand, which constitutes the chief producing horizon of the pool, is considered to be a delta deposit. The sand body was laid down during the Cherokee epoch at about the same time as the widely distributed Bartlesville sand was laid down to the east of this area. It is not considered to be strictly identical or continuous with it. The thickness of the producing horizon ranges from 50 to 80 feet. The oil sand is defined as a fine-grained calcareous sand, which is interstratified to some degree with thin beds of blue or brown shale. The reaction of wells when drilled deeper indicates that the producing zone is definitely broken into several distinct horizons by these partings. The productive thickness is considered as being between 25 and 40 feet in the majority of the wells.

The structure at Burbank resembles that of many other parts of the Osage Nation. The outcropping beds of limestone show the presence of a number of small and irregularly placed domal and basinal

---

[1] Data on Burbank pool mainly from:

Sands, J. M.: Burbank Field, Osage County, Oklahoma, A. A. P. G., Bull. No. 8, pp. 584–592, 1924; and Bull. No. 11, pp. 1045–1054, 1927.

Melcher, A. F.: Texture of oil sands with relation to the production of oil, A. A. P. G. Bull., No. 8, pp. 716–739, 1924.

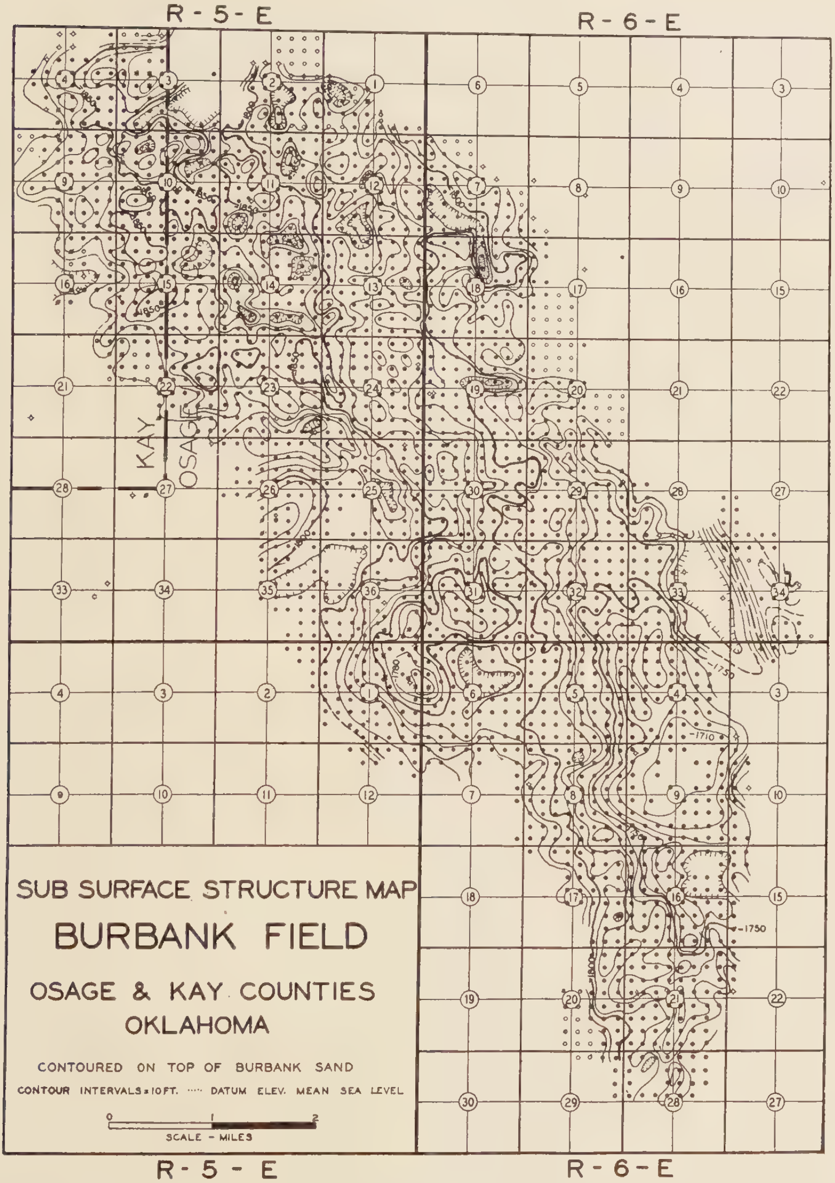

R-5-E
R-6-E
KAY
OSAGE
SUB SURFACE STRUCTURE MAP
BURBANK FIELD
OSAGE & KAY COUNTIES
OKLAHOMA
CONTOURED ON TOP OF BURBANK SAND
CONTOUR INTERVALS = 10 FT. ····· DATUM ELEV. MEAN SEA LEVEL
0 1 2
SCALE - MILES
-1710
-1750
-1750
R-5-E
R-6-E

FIG. 100.—Contour map on the top of the producing horizon in the Burbank pool. After Sands, J. M.: A. A. P. G. Bull., Vol. 11, p. 1049, 1927.

areas upon a westward sloping monocline. Small closures were found in Section 9, T. 26 N., R. 6 E. and in the northwestern corner of Section 6 of the same township. The latter closure extended into the adjacent sections as well. Despite the fact that the producing horizon was 2,800 feet below and near the base of the Pennsylvanian, these minor domes were found to be reflected in the contours drawn upon that horizon. As is usual throughout the Osage area, the reverse or eastward dip is somewhat greater in the deeper horizons, making the closures somewhat larger. In this case the closures reached a vertical extent of about 30 feet.

Judged solely from a structural standpoint, the production of the areas within the closures should have been greater than that from the less favorably located areas to the north of them. Yet this is not shown in the production figures that have been compiled.

TABLE 56.—TABLE SHOWING RELATIVE PRODUCTIVITY OF DIFFERENT PORTIONS OF THE BURBANK POOL.*

Section	Date First Well Drilled In	Total Production to Dec. 31, 1923	No. Wells Completed to Dec. 31, 1923	Production per Acre	Length of Time Producing	Subsea Elevation Top of Sand
		Bbl.		Bbl.	Months	
1. 9-26-6	Sept., 1920	2,234,698	44	3,500	40	−1,710′
2. NE. 1-26-5 NW. 6-26-6 SW. 31-27-6 SE. 36-27-5	Dec., 1920	2,261,320	63	3,500	37	−1,780′
3. 30-27-6	Aug., 1921	2,996,053	64	4,700	28	−1,800′—−1,840′
4. S.½ 24-27-5	Oct., 1922	3,591,482	32	11,500	15	−1,820′—−1,880′
5. NW.¼ 24-27-5	Apr., 1923	2,075,320	13	13,000	8	−1,820′—−1,880′

* After Sands, J. M.: A. A. P. G. Bull., Vol. 8, p. 588, 1924.

While the higher portions of the producing area contained greater amounts of gas than the lower ones, there was no definite gas area. The gas appeared to have been distributed rather uniformly throughout the whole of the area. However, there was reason to believe that communication between the different portions was not easily accomplished. The lessening of the gas pressure in one place through rapid recovery of the oil appears to have little or no effect upon the pressure in portions of the horizon only half a mile away.

From the lack of conformity between structure and production and the failure of the gas pressure to become equalized quickly, it may be concluded that communication between different parts of the horizon is difficult, and that despite the apparent continuity of the horizon as a whole there are wide and important variations in its porosity. To the west and south the limits of the productive area are defined by salt water; to the east, it is no less definitely terminated by tightening of the sand horizon and gradual change into impervious material. According to Melcher[1] the diameter of the grains in the producing sand becomes less toward the eastern edge of the pool until it finally merges into a shale. Determinations of the pore space of an edge well in this eastern portion, which yielded a maximum production of 25 barrels daily, show a porosity of from 13.7 to 15.3%. On the other hand, tests of samples from one of the largest wells in the center of a large productive area yielding wells of several thousand barrels initial capacity showed pore space ranging from 27.8 to 32.7%.

Minor Producing Areas.—The productive areas just discussed have been of the more important types. Variations in porosity may be even more striking in their effects in less sensational areas. One of these, a producing area in T. 27 N., R. 10 E., Osage County, Oklahoma, appears to be of sufficient interest to warrant some discussion. The productive area, according to Robinson and Mills,[2] occupies parts of Sections 11, 12, 13, 14, 15, and 23. It corresponds almost exactly with a synclinal area that is largely surrounded by anticlinal sections. The productive horizon is a stray sand lying between the Little Lime and the Big Lime, two distinctive Pennsylvanian horizons encountered in drilling. Its maximum recorded thickness is 96 feet and the average thickness throughout the productive area about 40 feet. Wells drilled to it were credited with an average production of about 40 barrels a day. The sand was reported as being very tight. It was found necessary to shoot the horizon with charges up to 200 and 300 quarts of nitroglycerin to obtain the full production.

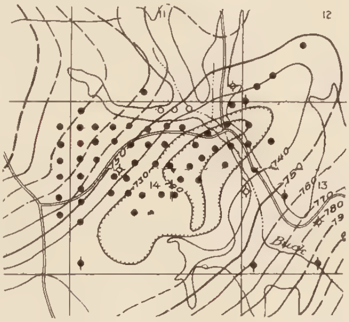


FIG. 101.—Productive area of stray sand in T. 27 N., R. 10 E., Osage County, Oklahoma. After Robinson, H. M., and Mills, R. V. A.: U. S. G. S. Bull. 686, Plates XLVI and XLVIII, 1919.

---

[1] A. A. P. G. Bull. No. 8, p. 767, 1924.

[2] Robinson, H. M., and Mills, R. V. A.: U. S. G. S. Bull. 686–V, pp. 303–327, 1919.

A number of wells have been drilled to stratigraphic depths considerably greater than that of the productive sand in nearby areas. In the Blaine dome to the north, and the Bellieu dome and the Herridge anticline to the south, gas and oil have been found in paying quantities. In none of these except the northeastern part of Bellieu dome is any oil reported in the stray sand under discussion. In some wells existence of the sand is recorded, but in others it does not appear in the driller's log.

Similar conditions are common in the various sands of the Devonian in western Pennsylvania. They are particularly marked in the Catskill formation in which rapid variations from sandy to shaly phases appear to be abundant. One of these occurring in the Foxburg Quadrangle has been mentioned by E. W. Shaw and M. J. Munn.[1]

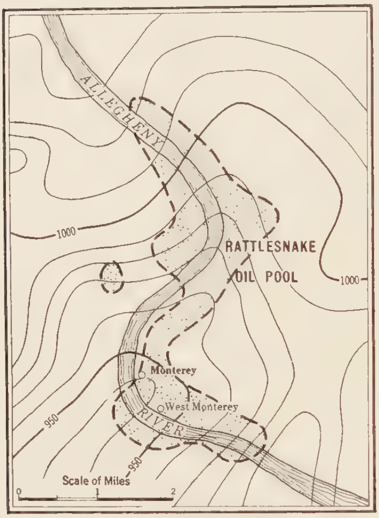


Fig. 102.—Structure map of the Rattlesnake pool. Adapted from Shaw, E. W., and Munn, M. J.: U. S. G. S. Bull. 454, Plate X, 1911.

The productive area was one of small size and was known as the Rattlesnake pool. Production was obtained from an area which was distinctly synclinal in form and came from a horizon that was correlated with the Hundred Foot sand. The same general horizon was productive in the Rosenberry pool four miles to the northeast. Structurally there seems to be no reason why the oil in the Rattlesnake pool should not have migrated up the slope to the general area of the Rosenberry pool. Salt water was found in contact with the oil in both places.

This was one of the conditions that led Munn to propose the hydraulic theory, which has been discussed in Chapter VIII. Increased knowledge of the nature of producing horizons and of the completeness of the separation which can be produced by variations in porosity makes it possible for us to consider that the absence of oil in the intervening areas and its presence in this synclinal basin were due almost solely to changes within the horizon itself.

---

[1] Coal, oil and gas of the Foxburg quadrangle, Pa., U. S. G. S. Bull. 454, 1911.

Pools at Unconformable Contacts.—Where the porous horizon into which the oil and gas have migrated is one that was formed from the untransported products of weathering or closely related talus material, its form may be expected to be of great irregularity. Such horizons are of major importance in the Panhandle structure of western Texas, the Healdton anticline, and a number of other recently discovered pools in the Mid-Continent Province. In most cases the form of the producing area is definitely arched, and in some cases production is obtained from overlying continuous beds. The discussion of such producing areas is, therefore, best taken up in Chapter XVII.

Where the sections that had been subject to erosion are submerged below sea level, their highest points may remain slightly above or below the water line. If the slopes of their sides are abrupt, they may have little effect upon the nature of the deposits laid down adjacent to them. Thus in deep waters, limestones may abut the ridges of older rocks. With shallower waters, shales and sandstones may be deposited. Oil and gas formed in such sediments would tend to migrate in the normal manner through their porous portions. On reaching the tilted and irregular surface of the eroded rocks, their migration would either cease or change materially. If the eroded surface was covered by porous products of the weathering, vertical movement might become very pronounced. If the older material was highly porous, the oil and gas would tend to enter it in large amounts. If neither base nor contact zone were of such nature as to permit migration, the movement of the oil and gas would terminate abruptly at the contact between the sediments and the older base. This has apparently occurred in a number of instances.

Sunset Extension, California.[1]—One case of such character occurs in the southern part of the San Joaquin Valley of California. The area is known as the Sunset Extension pool. It is one of the minor producing sections in Kern County.

The productive belt lies in the foothills of the Temblor Range and has a length parallel to that range for a distance of about two miles. Its greatest width is only one mile. Several wells were drilled just before the close of the last century. The oil was of low grade; and as the wells were small producers, the section was not developed. In

---

[1] Rogers, R. A.: Sunset Extension Field, California Oil Fields, Vol. 9, No. 12, pp. 18–24, 1924.

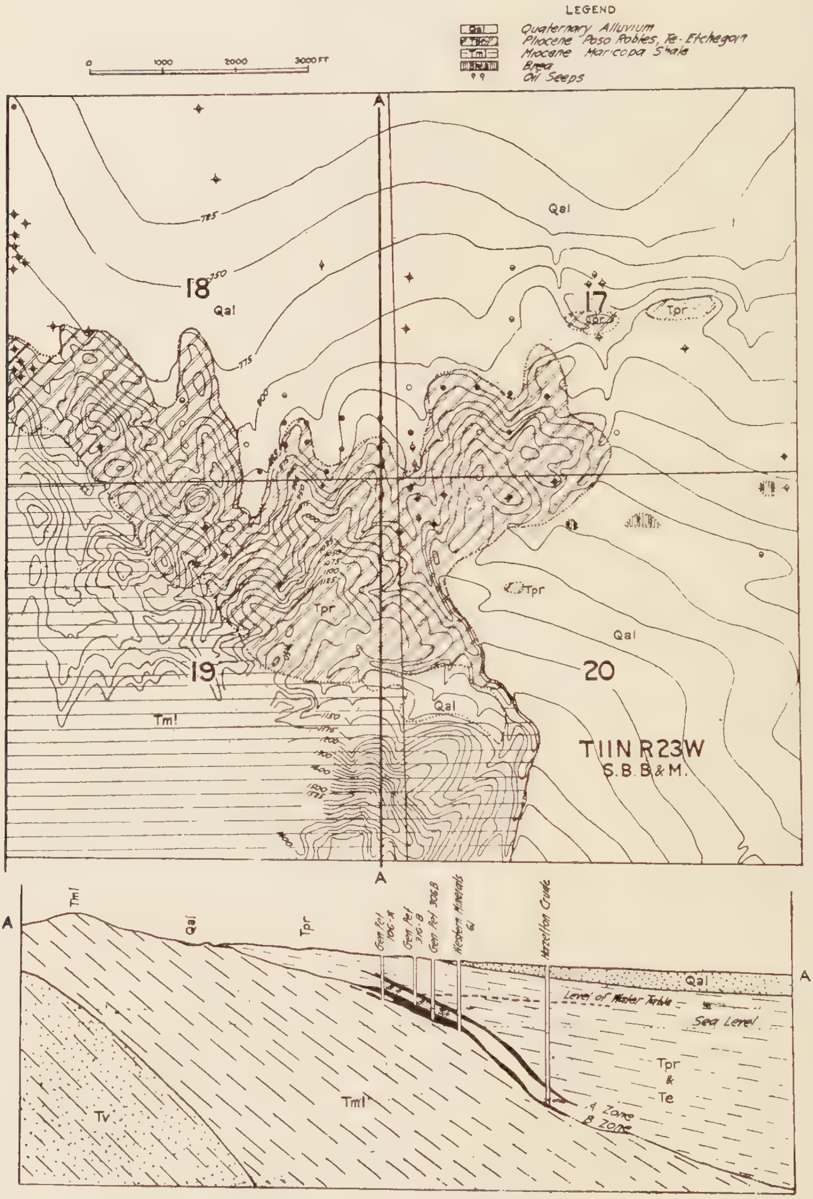


FIG. 103.—Sunset Extension Pool. Topography, surface geology and ideal section. After Rogers, R. A.: California Oil Fields, Vol. 9, No. 12, p. 21, June, 1924.

1922 better prices made operations commercially feasible and a number of wells were drilled in that year and shortly afterward.

The formations present are the surface alluvial material of the valley, the McKittrick formation, and the Maricopa shale. The McKittrick formation is divided into upper and lower parts, known respectively as the Paso Robles and Etchegoin. The Paso Robles member consists of a series of poorly consolidated sandstones, clays, and sandy shales. It dips northward at the rate of 20 degrees. The Etchegoin consists of porous sands partly separated by shales. It lies directly upon the tilted surface of the Maricopa diatomaceous shales. In these the northward dip is at the rate of 50 to 63 degrees.

The Paso Robles overlaps the Etchegoin. This fails to outcrop in this vicinity and pinches out to the south between the Paso Robles and the Maricopa. As both of these formations are composed mainly of shales, a definite trap is formed. The accumulation in the Etchegoin is complicated by the fact that it is not a single sand body but a series of sands interstratified with hard shells and beds of brown and blue clay. The final position assumed by the oil is therefore somewhat different from that which it would have taken had the porous horizon been more definite in outline. A slight change in dip from due north to northwest seems to have been of some importance in localizing the accumulation.

Maikop, Russia.[1]—A Beeby Thompson considers the productive area at Maikop on the northern slope of the Caucasus Mountains to be an excellent case of accumulation of oil in the highest portions of sands which had been deposited upon a tilted and folded base. The production from this area, while not comparable with that obtained

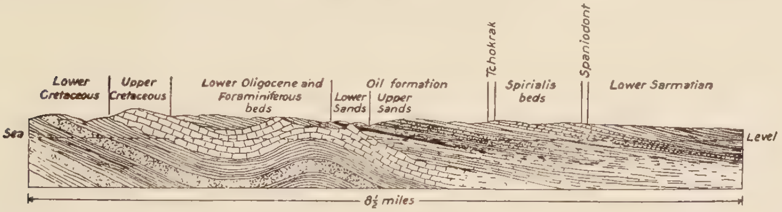


FIG. 104.—Section through Shirvanskaya wells, Maikop pool, Russia. After Thompson, A. B.: Inst. Min. & Met. Trans., Vol. 20, p. 229, 1911.

---

[1] Data on Maikop mainly from:

Calder, William: The Maikop Oil Field, South Russia, Inst. Min. Eng. Trans, Vol. 48, pp. 321–347, 1915.

Thompson, A. B.: Inst. Min. & Met. Trans., Vol. 20, pp. 229–230, 1911.

from Baku or even from Grosny, was equal to more than a million barrels in 1912.

The productive sands are of Tertiary age and rest upon the underlying Cretaceous strata. The area has been subjected to continuous overlap by the seas. The lower parts of the Tertiary strata terminate abruptly in contact with the Cretaceous; the upper overlie the whole area without reference to the form of the underlying Cretaceous. In the unexposed sands abutting the Cretaceous, the conditions were favorable for accumulation and retention. It is from these that the oil has been taken.

Channel Deposits.—Thin sand bodies may be deposited in channels by different agencies under different conditions. The two most probable agencies are the waters of tidal currents and rivers. The tidal channel system of a lagoon presents an ideal area for the deposition of lenticular bodies of sand. Such channels are apt to be meandering in character and greatly branched because of the flatness of the area over which the waters flow. Extreme lenticularity with numerous local variations into shaly matter may be anticipated in such areas.

Rivers deposit sand in their channels in varying percentages according to the slopes of their courses and the character of the material which they are transporting. Where the river is any distance above the elevation of the permanent base level, the deposition of the sand must result in deposits that are largely of temporary character and likely to be removed shortly after their formation. If the deposition occurs close to sea level and is followed immediately by a period of subsidence sufficient to bring the level of the area below the range of the most active sorting action of the waves, the river sand bar and other related forms of channel deposits may be preserved indefinitely. The formation of such deposits may be considered as being encouraged by oscillating movements of the shore lines during periods of deposition. Slightly uplifted, partly consolidated sediments of recent deposition are easily cut into by streams and relatively deep channels formed in sections of low relief. If the emergence is followed by submergence, the decreased carrying power of the streams will naturally result in the deposition of sands in these channels. Further subsidence will tend to change the character of the deposits and permit clays to be laid down over the whole of the area.

If the period of the emergence is short and the clays are deposited under similar conditions to those existing before the emergence, the evidence of the uplift may be practically obliterated. Determination of the areas in which the porous sands occur and are therefore most likely to contain oil and gas is naturally a costly and difficult problem. The only indication of the existence of the channel sands is furnished by actual drilling into them. If rivers and tidal channels were straight, some projection of their courses might be possible; but the winding form of the main streams and the complicated arrangement of distributaries and tidal channels, which are normal to low-lying coastal plains, are not conducive to such projections.

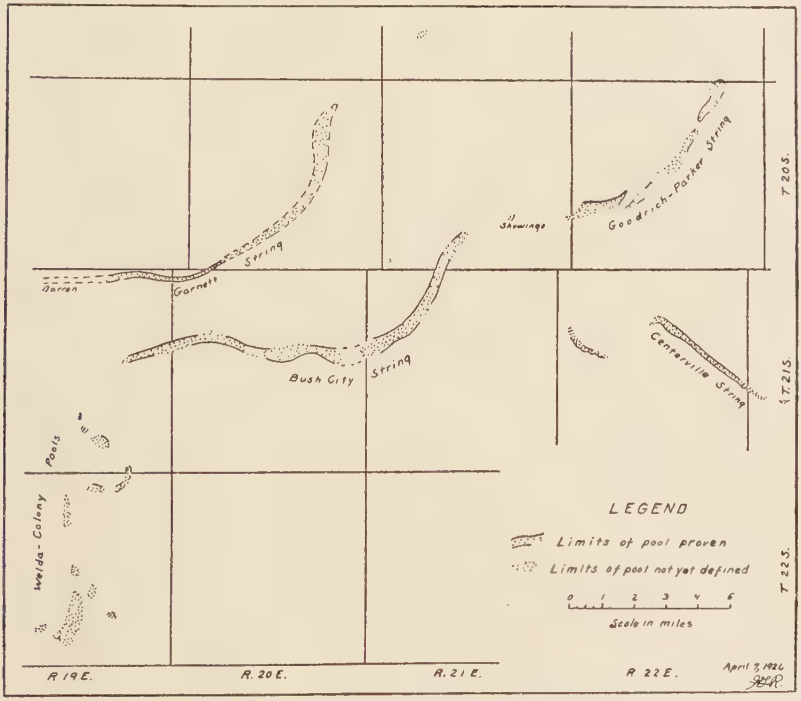


FIG. 105.—Shoe string oil and gas pools of Anderson and Linn Counties, Kansas. After Rich, J. L.: A. A. P. G. Bull., Vol. 10, p. 569, 1926.

"Shoe String Sands," Eastern Kansas.[1]—While not as large producers of oil as a series of similar deposits to the west of them, a series of channel deposits known as the "shoe string sands" of eastern Kansas are of considerable interest. These unusual sand bodies lie close to the top of the Cherokee shales of Pennsylvanian age. The sand bodies occupy what were apparently sharply cut channels in the underlying shales. Some thicknesses of over 100 feet have been measured, but more commonly the bodies are less than 50 feet in thickness. The shoe strings vary in width up to half a mile and have been traced over as great a length as 15 miles.

---

[1] Data from Rich, John L.: Shoe String Sands of Eastern Kansas, A. A. P. G. Bull., Vol. 7, pp. 103–113, 1923; and Further Observations on the Shoe String Oil Pools of Eastern Kansas, A. A. P. G. Bull., Vol. 10, pp. 568–579, 1926.

According to Rich, the Bush City string has a known length of eleven and one-half miles. The dip of the sand is the prevailing west dip of the section in which it occurs. Thus the bottom of the string lies at a depth of 640 feet at its eastern end and at 840 feet at its western extremity. The cross section of the sand body shows a channel filling about 50 feet. The basal, five to ten feet, are made up of black, somewhat shaly, pyritiferous sand. Above this there are 20 feet

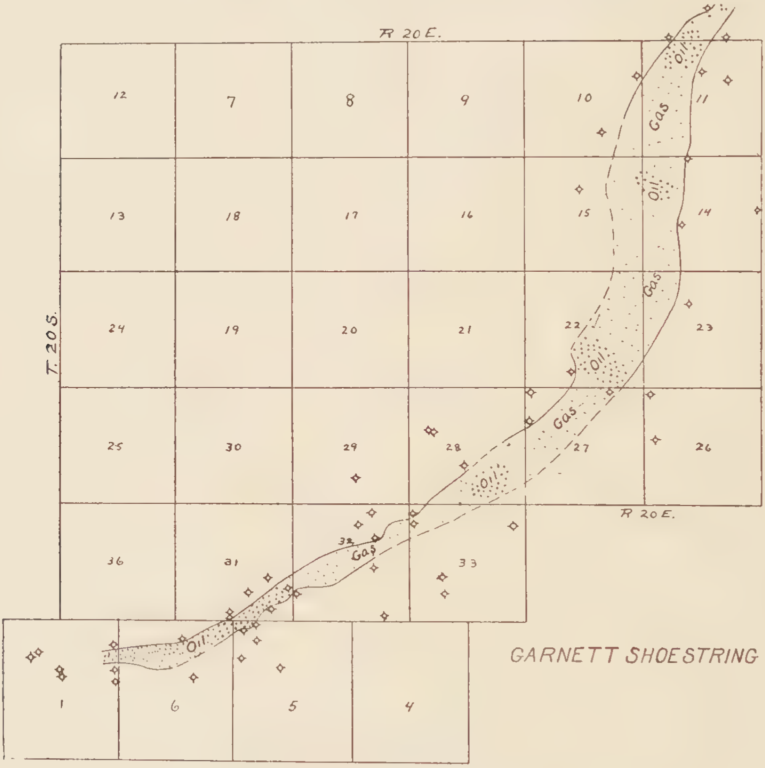


FIG. 106.—Development of the Garnett shoe string, Eastern Kansas as of December, 1922. After Rich, J. L.: A. A. P. G. Bull., Vol. 7, p. 106, 1923.

of relatively clean sand containing the bulk of the oil. The sand then becomes shaly again; and although oil-bearing, the next 10 to 15 feet are of little value. The uppermost portion, from five to 15 feet in thickness, consists of white micaceous, talc-like shale, which may be sandy in some areas.

Dry holes mark the edge of the string. Those close to the string reported the finding of the upper white shale but passed directly into the blue shales of the Cherokee and failed to strike the sand itself. The distribution of the clean sand is not regular in the Bush City string but thickens and thins in an irregular manner. No water has been found in the string at any point. The degree of saturation in the oil-containing parts does not appear to have been high.

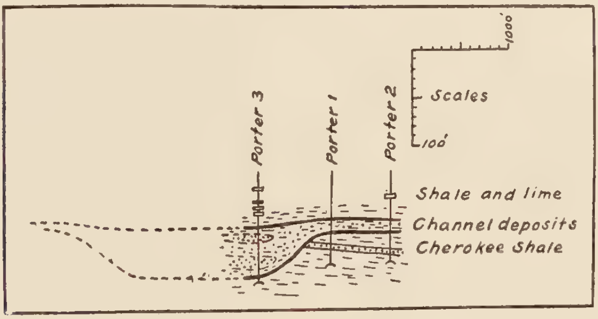


FIG. 107.—Typical cross-section of the Bush City shoe string, Kansas. After Rich, J. L.: A. A. P. G. Bull., Vol. 10, p. 571, 1926.

The confinement of the oil to the string necessarily limits the manner of its occurrence. The absence of water throughout the area discussed by Rich is difficult to explain, especially as it has been found in other similar strings. The best production in this string came from the highest parts of the trap, namely from Sections 18, 8, and 5 of T. 21 S., R. 21 E., where several wells of 200 barrels daily capacity were drilled. A minor structural high in the eastern half of Section 15 of T. 21 S., R. 20 E. is reported to have been more productive than the parts of the string adjacent to it.

In the related Colony string, gas and water have been found. The greatest accumulation of gas was found in a prominent northwestward plunging anticline. In the Garnett string no water has been found. Gas was most prominent in the higher eastern portions and oil in the lower western portions. The area to the west of the oil-yielding part of the string is like the Bush City string in that it yields no water and merely a trace of oil. This condition is repeated in the Goodrich-Parker string.

Large Elongated Sand Bodies.—In Greenwood County[1] in Kansas, in Washington County of Oklahoma, and in sections immediately adjacent to them, are a series of sand bodies that appear to be closely related to those of eastern Kansas just discussed. They are considerably different from them in being of much greater average width and reaching greater thicknesses. In addition, they are considered to have been laid down somewhat earlier. While a number of shoe string-like bodies have been discovered, the best known are the Sallyards-Madison shoe string in Greenwood County and the Hogshooter in Washington County. The first extends for a length of about 50 miles in a northeast-southwest direction. The second has been traced for about 45

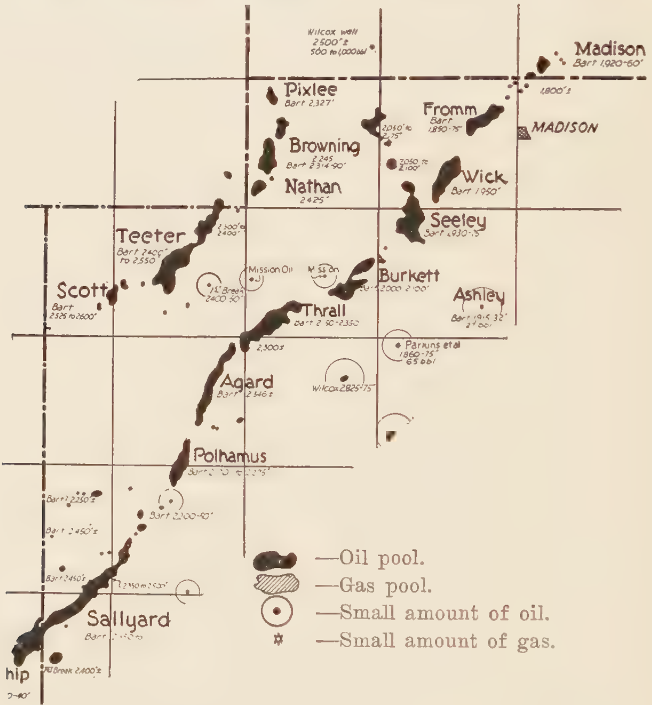


FIG. 108.—Map of shoe string pool area in Greenwood County, Kansas. After Oil and Gas Journal, Oct. 22, 1925, insert map.

---

[1] Cadman, W. K.: The Golden Lanes of Greenwood County, Kansas, A. A. P. G. Bull., Vol. 11, pp. 1151–1172, 1927.

miles in a north-south direction. While usually narrower, the Hogshooter attains a width of five miles in places. The maximum for the Sallyards-Madison is about the same.

The great extent of these sand bodies naturally arouses questions about their origin. Their position and relations with adjacent sediments suggest that they were laid down upon an eroded early Cherokee surface. The form of this surface, while partly due to erosion of a thin layer of sediments formed during a short period of shale deposition during the earliest part of the Cherokee, was considered as reflecting more closely the forms resulting from erosion between the close of deposition in the Mississippian and its beginning in the Pennsylvanian. While there is sufficient evidence to warrant the feeling that the small offshoots to the main sand bodies are true channel deposits, there is not enough to determine definitely that they are either stream- or tidal-channel deposits. Similarly it is not possible to determine from the evidence offered up to the present whether the main sand bodies are river deposits or examples of somewhat unusual sand bars. The author personally inclines to the view that they are of the river-channel origin.

Geologists who have worked in these areas are practically unanimous in stating that accumulation is controlled mainly by the form of the sand bodies and by the topographic contours of their upper surfaces. Because of their size, however, structural considerations cannot be disregarded entirely and tend to assist materially in determining the localization of the productive areas.

Hogshooter String.—The Hogshooter sand of Washington County, Oklahoma, has been described by Walter R. Berger,[1] who considers it to be a channel-sand deposit of river origin. The productive sand is commonly known as the Hogshooter gas sand after a large pool of the same name. The sand body varies from one to five miles in width over its length of 45 miles. The sand was found in a trough-like depression in the cherty limestones of the Boone formation of the Mississippian. Immediately above it are shales of the Cherokee formation of Pennsylvanian age. The maximum depth of the sand body was recorded as 168 feet. The thickness varies considerably, being greatest at the center of the channel and pinching out at the sides. Locally the sand body branches out to the east and to the west in the general form that might be expected where tributary streams enter the main stream.

[1] A. A. P. G. Bull., Vol. 3, pp. 212–216, 1919.

The more definitely outlined pools are the Hogshooter gas pool, the Burgess oil pool, and the Vander pool. The Hogshooter gas pool is 12 miles long by one and one-half miles in width and extends northward from the west-central part of T. 24 N., R. 14 E. The Burgess pool is two miles north of this and has a length of four miles parallel to the direction of the channel. It is only about a mile wide. North of the Burgess pool a number of wells have been drilled and a scattered production developed. There is one minor pool in this area. About 12 miles north of the Burgess pool, the important Vander pool was discovered. South of the Hogshooter gas pool, the Boone and the Cherokee formations diverge, other beds coming in between them. The trace of the ancient channel is not as clear in this section as to the north but is believed to be responsible for the location of some productive areas.

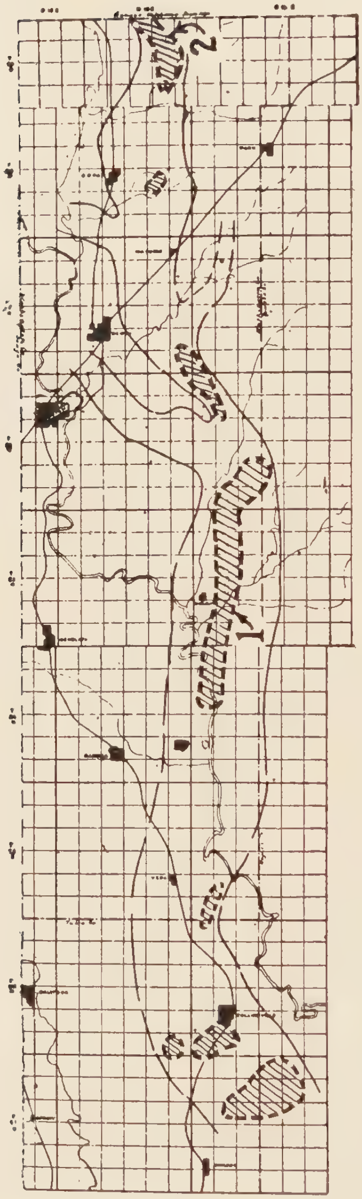


FIG. 109.—Map showing extent of Hogshooter sand, Oklahoma. 1. Hogshooter pool. 2. Vander pool. After Berger, W. R.: A. A. P. G. Bull., Vol. 3, p. 215, 1919.

In so large a body of sand as this, the slight south component of the normal southwest dip of the region has not been sufficient to cause continued migration to the northern or higher portion of the sand. Local structural conditions, resulting from folding, have caused the accumulation to follow the structural lines to a considerable extent. However, the borders of the sand body so definitely restrict the areas of possible production from this horizon that structure must be considered as of much less importance than the form of the sand body.

Summary.—Similar conditions are known to exist in the Sallyards-Madison string where at least 10 distinct producing areas have been developed. The same conditions are considered to control production in the less definitely outlined Scott-Teeter-Pixlee and Fox-Bush-Eastman areas in Kansas. Whether they have been of major importance in determining productive areas in the Appalachian field, in which depositional conditions were much the same, is not definitely known. The development of that area came largely prior to the development of geology as a science. The large number of productive horizons and the failure to make proper correlations during development make studies of causal factors difficult. The same condition has held in most of the world's fields until very recently. As the first essential to study of such conditions is accurate subsurface data, the fund of good examples that can be cited is very limited at present. This is true not only of the channel deposit accumulations but also of all of the other types that have been discussed in this chapter. It is the feeling of many geologists, including the author, that the more thorough studies which are being made today, combined with increasing knowledge of the underlying conditions that control accumulation, will demonstrate that such conditions have even greater importance than they have been credited with.

Production from Fissures.—The effects of jointing in the development of porosity were discussed in Chapter VII. Fissures and crevices resulting from dynamic stresses appear to be of major importance in determining the sections in which solutional agencies can develop high porosities such as are needed in container rocks. It is seldom that the joint or fracture plane develops into a fissure of sufficient size to be of economic interest unless such activity is also present. Detailed examinations of a number of cases in which oil and gas were believed to have come from fissures in shales and clays indicate that the sources were actually sandy lenses within those bodies.

In a few, the inability to find any difference in the composition of productive and non-productive portions and the erratic behavior of the wells give definite indication that the oil and gas are being taken from true fissures. In most cases fissure production is associated with production from the normal types of containers, sands and limes. It is commonly found in shales immediately overlying such horizons. The production is commonly subordinate to that obtained from these. Thus while fissure wells have yielded a considerable quantity of oil at Salt Creek, Wyoming, the main source of the oil has been the true sandstones.

The San Felipe shales overlying the Tamasopo limestone in the Panuco and Tamasopo Ridge areas of eastern Mexico have been fractured badly by the intense dynamic movements that have occurred in those areas. They have been productive of large amounts of oil in many wells, but their total production is not comparable with that of the underlying porous limestone. Shale wells in both Salt Creek

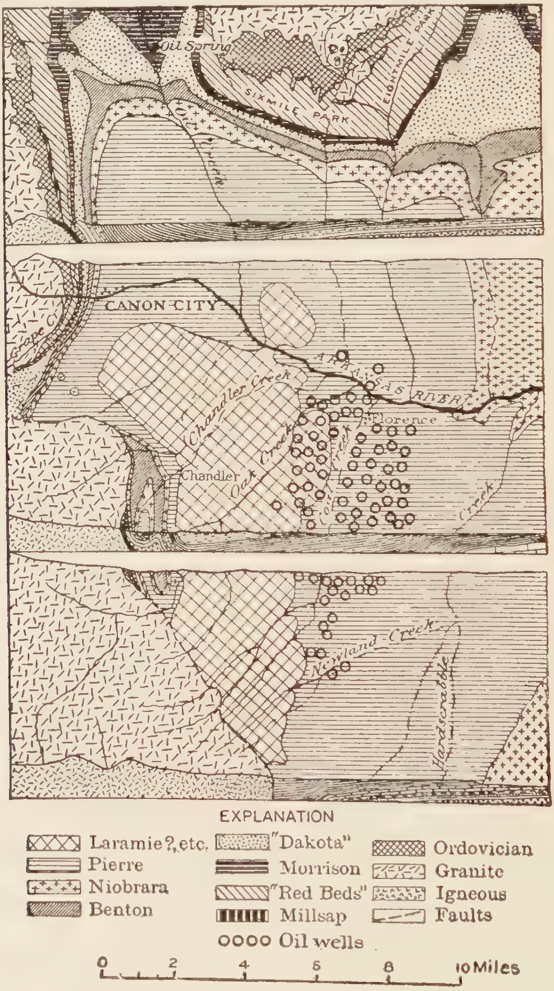


FIG. 110.—Geologic sketch of the Canon City Embayment, Colorado. After Darton, N. H., and Washburne, C. W.: U. S. G. S. Bull. 381, p. 518, 1910.

and Mexico have been extremely erratic in behavior. In the great majority of cases initial gas pressures and yields have been high, but declines have been extremely rapid. The rapidity of decline is not absolutely certain, however, some of the shale wells producing commercially for years.

In these and most other areas producing oil from shales, the close proximity of sand or lime production of much greater importance leaves little doubt concerning similarity in origin. Even though the crevices do not appear to be connected with the underlying sands and porous limes today, the previous existence of such connections appears probable.

At Florence,[1] in the Canon City embayment or synclinal area east of the Front Ranges of Colorado, shale crevices appear to be the only source of oil. Sands do not appear as producing horizons, the productive zone, though 2,500 feet thick, being composed entirely of shales. The crevices which yield the oil occur in the Pierre shales. Close to the surface the fissures contain waters that have migrated downward. Very little water has been found with the oil, though considerable has been found by wells that reached the underlying Niobrora formation.

The oil has been taken from a number of related but not in the main connected fissures. Individual fissures or crevices appear to have considerable vertical and horizontal extent. Their positions have been found to correspond in a general way with the positions of joints and folds noted on the surface. Drainage of producing wells by others striking the same fissure at lower depths has been of common occurrence. Wells that were located similarly with respect to the strikes of fissures have given similar yields. Others close to producing wells but farther away from the strikes of the fissures have missed them entirely and produced no oil.

The original source and the manner of accumulation of the oil in this area are not known. Several seepages of oil and areas of solid bitumens have been found in nearby sections in which sand horizons underlying the Pierre shales outcrop. From this it would appear that the oil may have migrated up into the crevices from below during a period when the crevices were more extensive and continuous than they are today. The absence of complete data on this and on other areas renders it impossible to make definite statements concerning either source or accumulation.

---

[1] Washburne, C. W.: The Florence Oilfield, Colo., U. S. G. S. Bull. 381, pp. 517–544, 1910.

CHAPTER XV.

IGNEOUS ROCKS AS OIL CONTAINERS.

Considerable attention has been paid to the possibilities of production in structures associated with igneous phenomena. Such accumulation may be thought of as of two types: first, accumulation in igneous rocks which, because of their porosity, form suitable container rocks; and second, accumulation in adjacent rocks due to the arching of such rocks by intrusive igneous bodies. The uplift that accompanies the intrusion of sediments by magmas in some cases is illustrated in the doming of sediments above laccoliths. While some oil-yielding domes have been suspected of being of laccolithic origin, this has not been definitely proved in any of the cases known to the author. The possibility, however, must be recognized.

Plug-like intrusions are known in the Tampico-Tuxpam embayment. These, together with intrusive dikes, pierce the sediments and uplift them to some extent. The arching of the strata resulting is conducive to the migration of oil within the strata toward these uplifted areas. The intrusions are without exception accompanied by much fracturing of the adjacent sediments. This, together with the shrinkage of the intrusive masses through cooling, tends to produce fractures in the sediments through which the oil may escape to the surface. Where neither the intrusions nor the prominent fracture lines associated with them extend to the surface, they may still be important factors in the concentration of oil and gas. The fissures form ideal channels through which these substances may move toward porous strata in which accumulation may be accomplished in the normal manner.

It would seem that the major function of the intrusive dike or plug is that of assisting in migration rather than acting as a direct agency of accumulation. The existence of some heavy oil in the surrounding sediments is to be expected, but commercially important wells can hardly be anticipated. In general, it is felt in Mexico, where dikes and plugs have been studied most in this connection, that the more desirable locations for testing are some distance from the igneous phenomena.

Furbero.[1]—The production of oil from igneous rocks that have high porosities is no longer unusual. One instance of interest is that of the production obtained from the Furbero structure at the extreme southern end of the Tampico-Tuxpam embayment area of Mexico. Here the Mendez shales have been intruded by a very thin laccolithic mass or sill, which has spread along the bedding planes of the already folded sediments. Those at Furbero had apparently been folded into the general form of an anticline. The intrusion evidently attained its greatest thickness near the crest of the anticline. This lifted the overlying beds and tended to accentuate the anticlinal structure in those horizons. The shales above and below the intrusion were highly metamorphosed. Above the apex the metamorphosed zone continues in the form of a pipe or chimney until it reaches the surface.

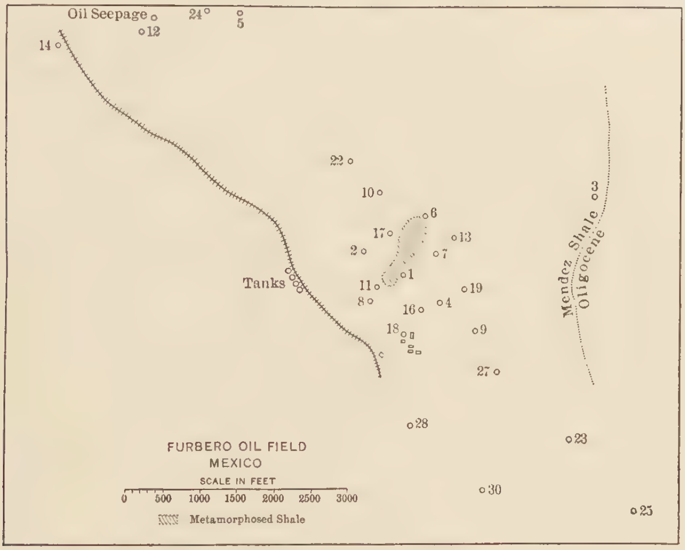


Fig. 111.—Sketch map of the Furbero Pool. After De Golyer, E.: A. I. M. E. Trans., Vol. LII, p. 269, 1915.

The metamorphism of the shales by the heat of intrusion and through the action of the gases and liquids that accompanied it has materially changed the character of the fine-grained, soft, blue to gray calcareous shales. In some places the product of the alteration is a hard black shale. Immediately above the igneous rock the shale is changed to a brown color and, while hard and silicified, is porous. The igneous rock itself is considered to be a coarsely crystalline gabbro or dolerite which has undergone extensive later alteration. The oil occurs in both the porous metamorphosed shales and the altered igneous rocks. Examination of a drill cutting of the latter showed a porosity of only six percent. As some of the wells have been fairly substantial producers, there is reason to believe that the pore space of the rock as a whole would be somewhat greater because of fractures. One well in the area was credited with an initial production of nearly a thousand barrels a day.

---

[1] De Golyer, E.: The Furbero Oil Field, Mexico, A. I. M. E. Trans., Vol. 52, pp. 268–280, 1915.

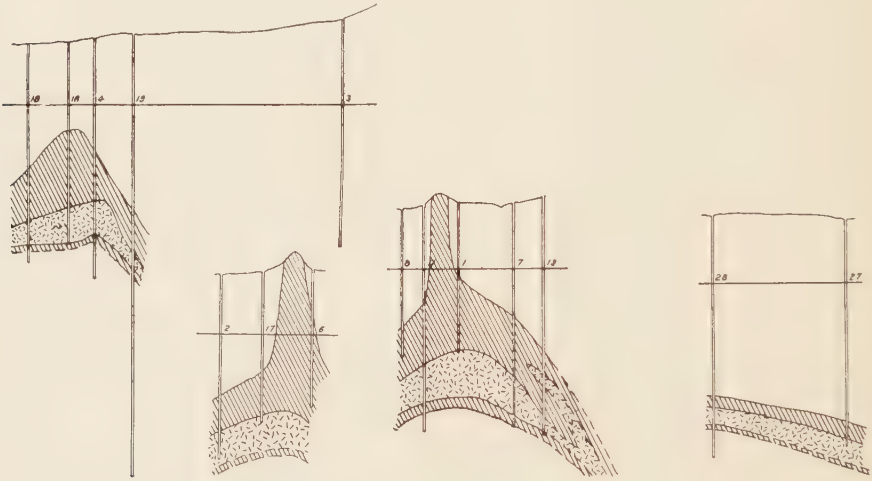
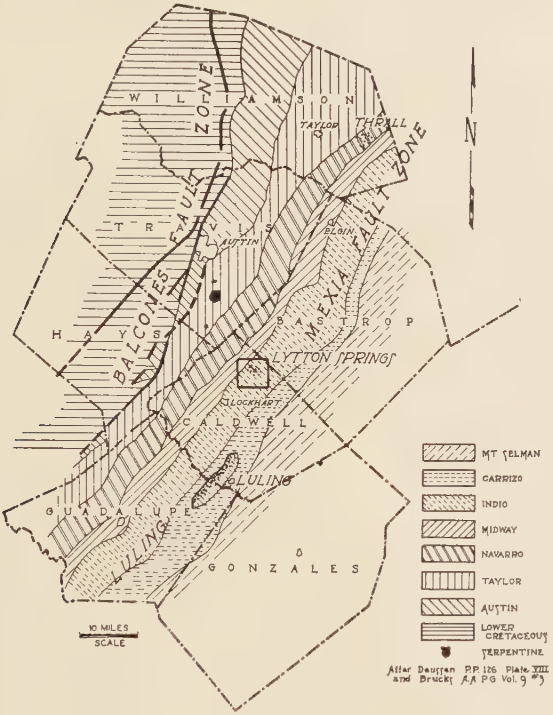


FIG. 112.—Group of Geological Sections, Furbero Oil Pool. After De Golyer, E.: A. I. M. E. Trans., Vol. LII, pp. 272–273, 1915.

Thrall and Lockhart.—The occurrence of oil at Thrall and Lockhart in Texas in "serpentine" has already been referred to. The productive areas in both pools were limited to the extent of the igneous bodies and further localized by variations in porosity and by the structural forms assumed by the bodies. The Thrall pool was discovered in 1915. The depth of the discovery well was 820 feet and its initial yield about 250 barrels. This shallow depth, together with the drilling of some wells with initial yields of as much as 3,000 barrels, led to rapid development of the pool. It produced more than 2,000,000 barrels of oil in the first two years of its life but rapidly declined after that. The rapidity of the development prevented the accumulation of much information desired by geologists.

No other pool yielding oil from a similar container was discovered until 1925, when the Lockhart or Lytton Springs pool was opened a short distance to the south of Thrall. The producing horizon here was somewhat deeper, the wells averaging from 1,200 to 1,500 feet in depth. The history of development was practically a repetition of that of Thrall, 325 producing wells being completed during the first year following the discovery. Four and a half months after the discovery the pool was producing 15,000 barrels daily, but the decline was rapid after that time despite the large number of wells that were completed. Some wells yielded more than 2,000 barrels daily for a short time, in spite of the relatively small quantity and pressure of the gas and the absence of edge and bottom waters to provide hydrostatic head.



After Deussen P.P. 126 Plate VIII and Brucks A.A.P.G. Vol. 9 #3

FIG. 113.—Geologic map of the Luling-Lytton Springs (Lockhart)—Thrall Area, Texas. After Collingwood, D. M., and Rettger, R. E.: A. A. P. G. Bull., Vol. 10, p. 954, 1926.

A third pool was discovered at Dale in the same area in 1927. It proved to be of smaller size than its predecessors.

The importance of the Lockhart discovery was quickly recognized by geologists and producers and every effort made to gather complete information about it. Several excellent descriptions[1] of the pool have been published.

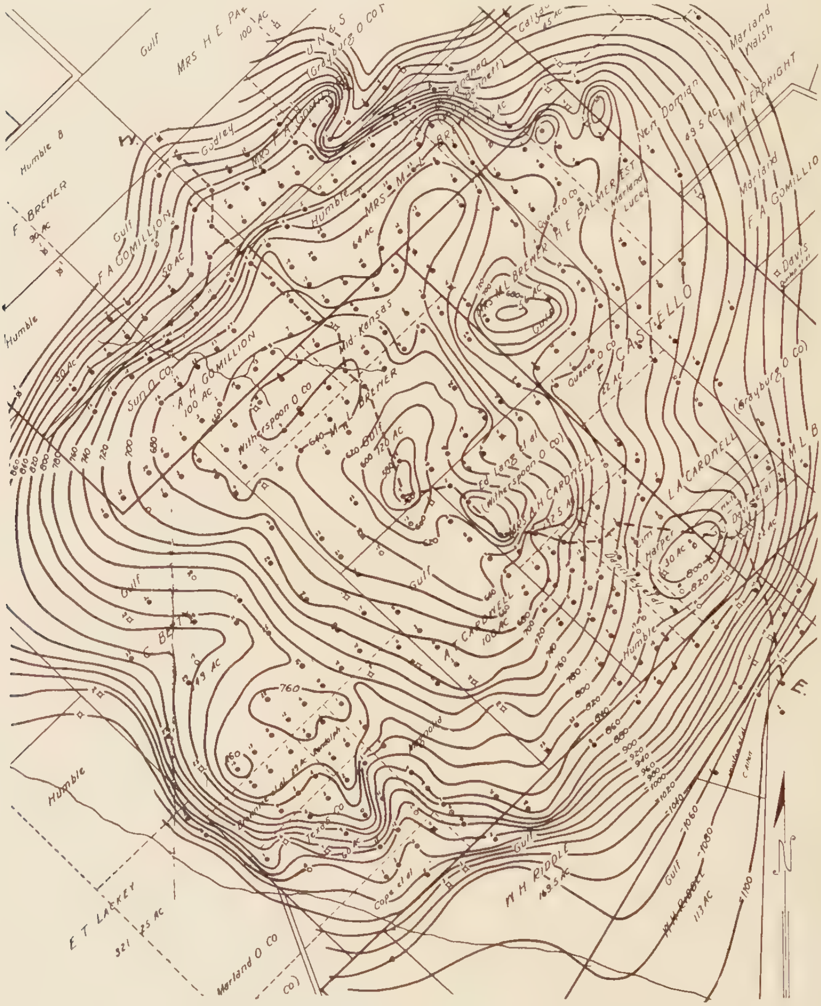


FIG. 114.—Lockhart or Lytton Springs Pool. Contour map showing position of the top of the serpentine. After Collingwood, D. M., and Rettger, R. E.: A. A. P. G. Bull., Vol. 10, insert opposite p. 959, 1926.

---

[1] Bybee, H. P., and Short, R. T.: The Lytton Springs Oil Field, Univ. of Texas Bull., No. 2539, Oct. 15, 1925; and Collingwood, D. M., and Rettger, R. E.: The Lytton Springs Oil Field, Texas, A. A. P. G. Bull., Vol. 10, pp. 953–975, 1926.

The pool lies between the Balcones and the Mexia-Luling fault zones. The surface formations are Tertiary. Below these lie Upper Cretaceous beds, including in descending order, the Navarro, Taylor, Austin, and Eagle Ford formations. Below the Eagle Ford lie the Comanchean horizons. These include the Edwards limestone, which is productive in the Luling pool eight miles to the south. The serpentine at Lockhart has risen to the level of the Taylor Marl and the Austin Chalk formations where it has spread out horizontally. Discoloration and metamorphism of the chalk at several points where it is in contact with the serpentine indicate an intrusive origin. This is further sustained by the doming of the overlying formations. On the other hand, the non-intrusive character of the contact between the serpentine and the Taylor Marl, together with the fractured and vesicular form of the serpentine, suggests a volcanic origin. It seems advisable to consider that the igneous body is partly intrusive and partly extrusive, and that its porosity is partly original and partly the product of alteration by circulating waters of surface origin.

The difference in elevation between the top of the serpentine at the center of the structure and at its edges is approximately 600 feet. This is considerably greater than the amount of folding in the overlying beds. The edges of the serpentine are interfingered with the sedimentary rocks. The serpentine has been drilled through in

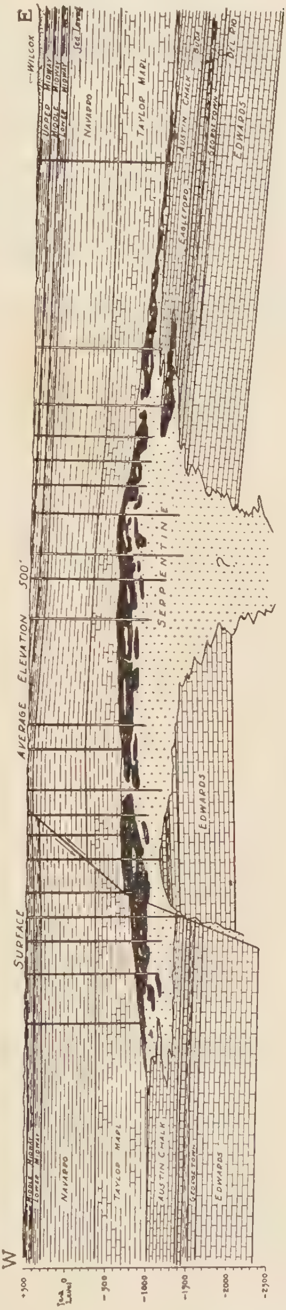


FIG. 115.—East-West Cross-section of the Lockhart or Lytton Springs Pool. After Collingwood, D. M., and Rettger, R. E.: A. A. P. G. Bull., Vol. 10, p. 959, 1926.

a number of wells and the underlying sediments disclosed. The thickness in the central portion of the body is not known. The productive portions of the serpentine are mainly in the upper 200 feet; but due to the wide variation in the position of the surface of the mass in different parts of the structure, this has resulted in obtaining oil from a vertical range of 700 feet. In several wells the porous oil-containing serpentine was not encountered until fingers of chalk lying between fingers of serpentine were penetrated. In such cases the production came from porous portions in the upper parts of underlying serpentine fingers rather than from the porous parts of the main serpentine mass.

The oil obtained is of 38.1° Baume gravity and is entirely different in character from that obtained at Luling. It is commonly considered to have been derived from some of the dark shales or marls in the Upper Cretaceous beds, which are in direct contact with the serpentine.

Akita and Related Districts, Japan.—Several of the producing horizons in Akita and other producing districts in Japan are considered to be of igneous origin. This is technically correct; but as sedimentary agencies have been of considerable importance in their formation, they cannot be considered as purely igneous in origin. These horizons consist of volcanic tuffs and tuffaceous sandstones.

TABLE 57.—OIL-BEARING TERTIARY STRATA OF THE AKITA DISTRICT, JAPAN.*

4. Uppermost Division.
    Clay, sand and gravel, unconsolidated.
        Unconformity.
3. Upper Division (Pliocene).
    Bluish gray sandstone with thin layers of conglomerate, 660 feet.
2. Middle Division (Miocene).
    b. Bluish gray sandy shale, 3,280 feet.
    a. Grayish shale with thin layers of tuffaceous and conglomerate sandstone in upper part, alternating sandstone and shale, 1,320 to 1,480 feet.
1. Lower Division (Miocene).
    c. Black shale with thin layers of tuff and tuffaceous sandstone, 1,650 feet.
    b. Brownish siliceous shale with layers of tuff and tuffaceous sandstone.
    a. Green tuff with lignite seams.

* After Redfield, Arthur H.: E. & M. J. P., Vol. 120, p. 331, Aug. 29, 1925.

They were probably laid down in shallow-water bodies during periods of volcanic activity and owe their present form and characteristics as much to the ordinary agencies of sedimentation as to their volcanic origin. In the same areas in which the tuffs are productive, ordinary sediments also yield oil and gas. Production is determined by structural conditions similar to those which apply in other areas.

Contact Zone Production.—Production from contacts of igneous rocks with sedimentary types is of some importance. In some cases the oil appears to be contained in the igneous rock itself. In most, the igneous rock surface is identified as the surface of an eroded area much older than the surrounding sediments. While uplifts have undoubtedly occurred in such masses after the deposition of the sediments in some areas, there is no evidence to indicate that they were accompanied by later igneous action that affected the accumulation of the oil. The presence of the oil in igneous rocks may be traced to the weathering and fracturing of their upper portions to form suitable reservoirs. The occurrence of oil in serpentine in contact with Jurassic and Cretaceous rocks in Cuba is probably of this type. Some authorities, however, hold the view that the serpentine is an intrusive with respect to these formations. Some of the oil and gas obtained in the Panhandle section of Texas probably comes from weathered and partly disintegrated granites and related rocks. The "granite wash" from which much of the production is taken must be considered as of sedimentary origin, despite the fact that it has been carried only a relatively short distance.

Summary.—While the discovery of more pools whose production comes from igneous rocks is to be expected, their relative scarcity warrants that they be considered as freak producers. The existence of the necessary porosity in igneous rocks that were originally formed at considerable depth implies alteration by agencies of surface origin. Those laid down on the surface are so closely related to normal sediments in most cases as to cause them to function in the same manner as such sediments. The importance of doming by the uplifting agency of the laccolithic intrusion remains to be proved; and, while its possibility is admitted, the absence of definitely proved examples makes it impossible to include it among several types of oil structures. The author cannot but feel that intrusion of beds subsequent to the formation of oil and gas will in the great majority of cases serve mainly to assist those substances to escape rather than to assist in their accumulation and retention.

CHAPTER XVI.

SALT CORE STRUCTURES.

The production of oil from strata associated with great stocks and ridges of rock salt is of major importance. The salt structure is the source of oil in the Tertiary field of southern Texas and Louisiana. Oil has been found in structures of similar nature in the Isthmus of Tehuantepec in Mexico. The oil-producing areas of Roumania are closely related to salt domes in that country. In Germany salt structures are productive in a small way. The salt dome, characterized by limited horizontal extent and great thickness as distinguished from the bedded salt deposit having the form of an ordinary sedimentary rock, is known in areas where it does not appear to be associated with oil. These include, among others, parts of Utah, Persia, and northern Africa. Until recently the interior domes of Texas and Louisiana were considered to have no oil possibilities. In the belts listed as containing oil and gas all of the salt masses are not productive of those substances. In the Gulf Coast territory of Texas and Louisiana some that do not yield commercial quantities of oil are productive of large amounts of sulphur.

Despite the large amount of research that has been done upon the subject, our knowledge of the properties of salt domes is comparatively small. This is particularly true in the Gulf Coast area and in Roumania where the most productive oil-containing structures are found associated with the salt masses. The explanation in the first case lies in their deep burial below sediments and in the second, to the extreme complexity of the tectonic movements that have occurred in the Carpathian foothills of Roumania. In contrast with the procedure of the previous chapters, where the principles were discussed first and their application given later, it seems necessary to describe the details of the salt bodies first and then give a brief summary of the most important theories that have been developed to explain their existence. Inasmuch as the salt domes and structures of North Germany have been more closely examined than any of the others, they will be discussed first. Their importance lies not so much in the production of oil and gas as it does in their value as sources of potash. To the oil geologist they are particularly interesting because of the fact that many of them lie close to the surface and have been penetrated by mines, something that has not been possible in the oil-producing salt structures of other areas.

The Salt Masses of Germany.—The salt beds of Germany formerly extended over a wide area. In the sharp tectonic movements that caused the uplift of parts of the area, the beds were folded and faulted. Much of the salt has been eroded. It still remains, however, in the Magdeburg-Halberstadt Basin, the Thuringia Basin, and the Rhone Basin. In these areas the salt is covered by Triassic, Jurassic, and in part by Cretaceous beds. To the north of the basins lie the Hanover and North German plains, areas in which the salt has not been elevated to so great an extent and only comes close to the surface in circular salt domes. Here the salt beds are buried below Tertiary sediments as well as those of earlier periods.

The German salt stocks or Salzstöcke are not isolated occurrences of salt like those of the Gulf Coast of the United States but are closely related to the ordinary salt beds or Salztafeln of the area. Between the true salt stock and the bedded type is the salt anticline called the Salzsättel. The salt beds are horizontally lying or slightly inclined deposits regularly intercalated between the Middle Zeckstein (Permian) beds below and the Buntsandstein (Lower Triassic) beds above. In the salt beds the individual strata are concordant with each other, and the salt formation itself is concordant with the overlying and underlying beds in a general way. The salt-containing strata show numerous series of intense folds with the frequent occurrence of overturned folds projecting into the strata above and below. Thinning and thickening of strata are common. The foldings are strictly local and die out both above and below the salt beds, although other beds are folded in a broad manner.

The transition from these salt beds with their various internal folds to the salt anticlines is slight. Here the salt beds and the formations above are arched up in the normal anticlinal form. While in some of the salt anticlines the folding is not accompanied by any material change in the outline of the salt beds, in others these beds show much more marked local folding than those of the horizontal type. Along with this is a general tendency toward marked thickening of the salt body in the anticlinal area. Where the thickened salt bodies have come in contact with ground water, the upper surface appears to have been leached of its salt content and to contain only the less soluble gypsum. This results in some cases in the formation of a solution trough or graben in which later sediments may have been deposited.

The thickening of the highly folded salt beds gives rise to a definite core area in the salt anticline. However, the core is overlaid concordantly by the strata of the overlying series, the Buntsandstein. The transition between the salt anticline and the salt stock (the salt dome of the American writer) involves the piercing of the overlying beds and the upward movement of the salt. This may, as at Benthe, show very little elevation above the original; or, as at North Hanover,

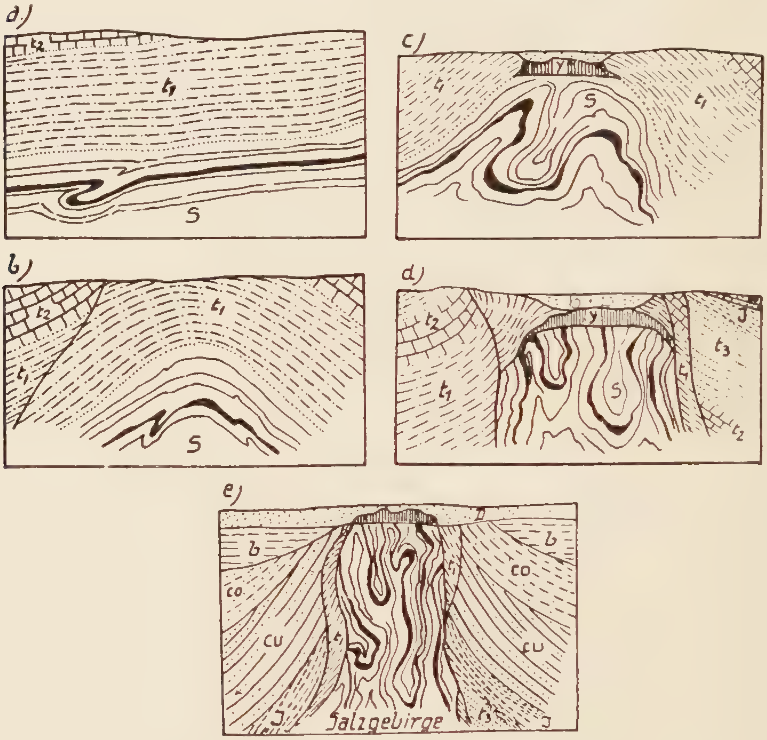


FIG. 116.—Tectonic forms of the occurrence of the German salt deposits: (*a*) "salt bed," south of the Harz; (*b*) salt anticline, South Hannover; (*c*) salt anticlines with "salt table," Hildesheim; (*d*) transition between salt anticline and salt stock, Benthe; (*e*) salt stock, North Hannover. Stratigraphic legend: *D*, Diluvium; *b*, Tertiary; *CO*, Upper Cretaceous; *J*, Jurassic; t_3, Upper Triassic (Keuper); t_2, Middle Triassic (Muschelkalk); t_1, Lower Triassic (Buntsandstein); *Y*, Residual gypsum cap; *S*, Salt formations with potash beds in heavy black lines; *CU*, Lower Cretaceous. After Stille, Hans: A. A. P. G. Bull., Vol. 9, p. 425, 1925.

the salt core may extend from the Permian source beds up through Triassic, Jurassic, Cretaceous, and Tertiary beds.

The salt stocks are circular, elliptical, elongated or irregular in cross-section. The sediments adjacent to them are at high angles to the horizontal. A flat gypsum cap is generally present. The flanks of the salt stocks are usually very steep, but moderate slopes are not unknown. In a few cases the salt constricts downward in the form of a funnel. In a few the downward constriction is so marked that the salt body is said to be without roots. Bedding lines may be followed easily in most of the salt masses despite the intense folding, thinning, and thickening, to which the salt has been subjected. This is marked proof of the high plasticity of the salt. The less plastic gypsum and clay beds originally associated with the salt were shattered and have allowed the salt to move upward through the breaks. The strata associated with the salt stocks show evidence of folding, but the degree of folding is not comparable with that of the salt masses.

Faulting is frequently associated with the domes. It has apparently resulted from two causes: first, as a result of stresses developed during the uplift of the salt masses; and secondly, as the result of slumping following solution of the upper surface of the salt.

Where the salt domes were not thick or deeply buried, the bottom of the salt mass has been reached and the underlying sediments have been penetrated. However, the thickness of the salt stocks in some places is very great. Donald C. Barton[1] gives the following record of wells that have stopped in salt.

HILDSCHEIMER WOLD DOME (NORTH WEST HARZ FORELAND).	Meters	Feet
Sülberg Boring	1,350	4,431
Salzdefurth No. II	1,400	4,595
SALT DOMES OF THE NORTH GERMAN PLAIN.		
Sperenburg	1,390	4,562
Salzwedel Boring No. IV Gastritz	1,390	4,562
Lubtheen	1,204	3,952
Altona, Lieth Boring	1,338	4,391
Wietze-Steinförde Prinz Adelbert No. IV	1,613	5,294

The Prinz Adelbert boring encountered salt at 109 meters or 323 feet, making its depth in salt greater than the American record made by the Texas Company, which struck the top of the dome at 1,340 feet in a well at Humble and stopped in salt at 4,400. The salt depth of the German test is even greater than that of this well combined with that of a second deep test that was located on the flank. The deep flank test encountered salt at 2,342 and continued drilling in salt to 5,410 where the test was abandoned.

---

[1] A. A. P. G. Bull., Vol. 9, p. 1254, 1925.

Roumanian Salt Domes.—The Roumanian salt domes occur in two groups. The first group parallels the Carpathian Mountains and is located along the edge of its more pronounced folds and in the Sub-Carpathian slopes. The second group lies in the Transylvanian Basin within the arc of the mountain ranges. The mountain system bends to form a semicircle extending from Galicia into central Roumania. The Carpathians are composed of two crystalline core areas, one near the northern end of the system, and the other in the southwestern part. Between these and especially to the east there is a zone of intensely folded Early Tertiary and Pre-Tertiary sediments. Folding has been accompanied by faulting. This is the zone of the highest ridges of the Carpathians and is called the Flysch zone. From the Galician border southward through Roumania the eastern rim of the mountains is bordered by a belt of Miocene strata, which show less intense folding. This appears to be a transition zone between the highly folded mountain areas and the largely unfolded Moldavian plain and plateau areas.

The Sub-Carpathian zone is characterized by open folds to the north. To the south where the trend of the ranges changes from the north-south direction to the east-west, the folds become more crowded. In the east in the vicinity of the Dambovitza River, the structure becomes very complex.

The salt domes of the outer zone of the Carpathians are largely restricted to the Sub-Carpathian area. A few lie along the eastern edge of the Flysch zone. The salt domes are large lenticular massifs. They are of high purity, but the presence of coloring matter gives rise to distinct stratification. Usually this is shown merely by alternation of light and dark lines or bands, but in some there are beds of argillaceous material also. These may contain carbonized debris of trees.

The salt bodies are parts of "diapir folds" or "outbreaks." The diapir fold, according to the definition by Mrazec, is one in which the beds of the core tend to pierce the overlying beds of the arch. The beds in the core dip more steeply than those in the adjacent sediments.

The outbreak is merely a continuation of the diapir in which the core intrudes vertically into the overlying sediments.

The flanks of domes are usually curved and steep. A large number of the domes reach the surface. The outcrops of many of them are circular. In others the outline of the core is oval. This is true at Gura, Slaniculiu, Moldova, and Ocnita. A number have sinuous or crescentric outlines. This type includes Targu-Ocna, Moreni, Ochiuri, Slanic-Prahova, Ocnele, Mari-Valcea, Martiia, Apostolache, Podenii, Noi, and others. The last group is by far the most important as their long outcrop lines represent the crests of more or less reclined and sometimes recumbent folds. The steeper side of the fold is away from the intense folding of the Carpathians. Where compression has been most intense, downward enlargement of the salt cores may not occur. In some the outcrop shows enlargement of the width of the salt body. In some cases the salt core has two peaks.

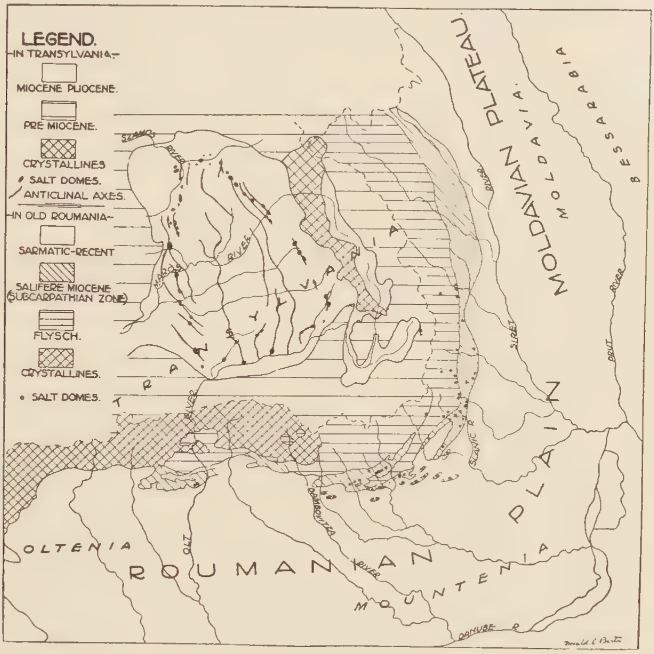


Fig. 117.—Geologic sketch map of Roumania showing location of the Transylvanian, Carpathian, and Sub-Carpathian salt domes. After Mrazec, Papp, and Böckh, adapted by Barton: A. A. P. G. Bull., Vol. 9, p. 1238, 1925.

Circular salt outcrops are frequently found to be small domal areas upon longer salt folds and to bear much the same position to the salt mass as the structural dome does to the anticlinal fold. This is especially true in the salt domes of Transylvania. At Baicoi-Tintea and Cacica-Bucovina the salt cores show peaks that are separated by a syncline of highly compressed sedimentary material. In the latter the sedimentary matter has been completely brecciated, the peaks being separated by the breccia. In a number of instances the breccia, while probably present originally, has been entirely obliterated except for rock inclusions within the salt mass.

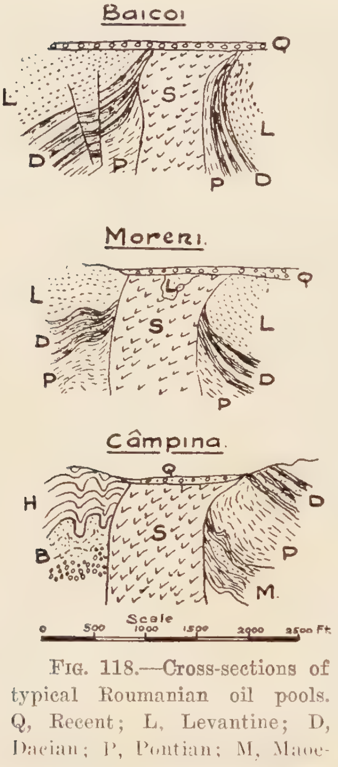


FIG. 118.—Cross-sections of typical Roumanian oil pools. Q, Recent; L, Levantine; D, Dacian; P, Pontian; M, Maeotian; H, Helvetian; B, Burdigalian; S, Salt. After Mason, S. L.: A. A. P. G. Bull., Vol. 9, p. 152, 1925.

Breccia similar to that found between the crests is also found around and above the salt mass. It is very evidently the product of the fracturing of the formations through which the salt has been pushed. The greater part of that found close to the surface is naturally of comparatively recent age. Eocene and Oligocene fragments predominate in the Flysch area. In the Sub-Carpathians the Paleogene-Miocene breccia is most common. Breccia is not found in all domes, however. In those of the southern Carpathians, such as Ochiuri, Gura, Ocnitei-Moreni-Bana, Baicoi-Tintea, and Floresti, the breccia is either entirely lacking or represented by extremely small masses. These domes occur in areas of Paleocene outcrops. Fragments of formations older than the Tertiary appear in the breccia in some cases, large blocks of Jurassic limestones having been reported in several instances.

Less is known of the domes contained within the Carpathian arc in the Transylvanian plain. The salt domes of that area intrude relatively flat-lying Miocene and Pliocene beds. These are moderately folded into anticlines and synclines whose axes generally trend north and south. The salt domes are circular or elliptical in outline; but as has already been pointed out, they have proved to be domed areas along larger long anticlinal folds in some cases. The alignment of known salt domes is definitely along structural lines.

Oil Production of European Salt Structures.—Small amounts of oil have been obtained from the Jurassic strata associated with uplifted salt masses in the Hanover district in Germany. Most of the wells have been of low yield and have produced a heavy oil of poor refining quality. A few have been of the gusher type when completed. All of them have declined rapidly. Some gas has been obtained in Transylvania within the arc of the Carpathians. However, chief interest in salt core structures as oil producers lies in the productive area south of the westward bending portion of the Carpathian Mountains in Roumania. This section has contributed practically all of the oil obtained in that country. The greater part of the oil has come from Pliocene strata. A little comes from the Oligocene. Some oil is taken from folded areas in which no salt cores are known to exist. The most productive areas are associated with outcropping salt masses and sections in which salt is found close to the surface. The oil is obtained from the highly folded and faulted strata on the flanks of the salt masses.

Isthmuthian Domes of Mexico.—The Salt dome area of Mexico lies in the southern portion of the state of Vera Cruz and immediately south of the town of Puerto Mexico. Oil production has been ob-

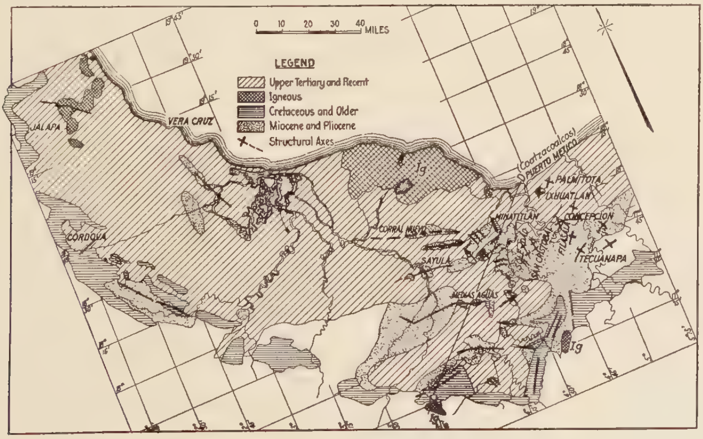


FIG. 119.—Map of the Isthmus of Tehuantepec, southern Mexico, showing location of salt domes and structural features. After Huntley, Stirling: A. I. M. M. E. Trans., Vol. LXIX, p. 1154, 1923.

tained at various times from at least six domes, but operations can hardly be considered as having been comparable in success up to the present with those in Texas, Louisiana, and Roumania. In the exploration of this area a large number of other domes have been tested, but with little success.

The salt domes of the area are of two distinct types, quaquaversal or cross-axes domes and elongated domes. The latter occur almost entirely west of the Coatzacoalcos River. The salt domes are considered to be in alignment by some writers, while others consider that no alignment can be proved. The oil taken from the salt structures has come from above the salt masses and most commonly from the dolomitic cap rock overlying the salt bodies. The dolomite appears to be extremely porous in some areas.

The uplift of the salt masses has evidently been of great extent. Massive Cretaceous limestones are frequently found at the surface surrounded by recent Tertiary sediments. In one dome near Chinameca known as Tonalapa, highly folded Triassic beds emerge from the Tertiary. In this area a test well entered the salt body a short distance from the surface. The Triassic matter appears to have been elevated about 6,000 feet. No Cretaceous lime was found at the surface in this area. Fossils and remnants of beds normally found at great depths were found in the Triassic-Tertiary contact zone indicating that brecciation of the material below the Tertiary had probably taken place. With the exception of the case mentioned there is no record of the drill penetrating the Lower Cretaceous limestone, which is so productive in the Tampico-Tuxpam Field. Practically all of the wells have stopped before reaching 3,500 feet. One at Filasola went to nearly 4,000 feet.

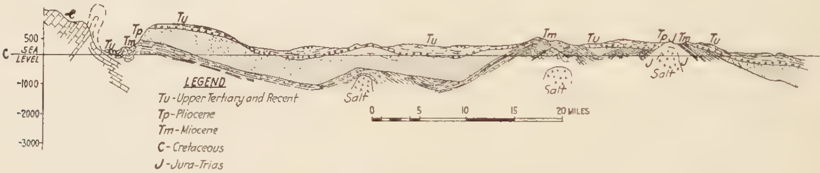
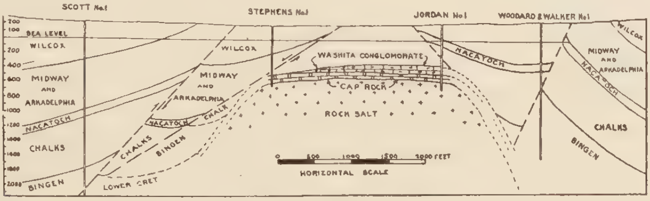


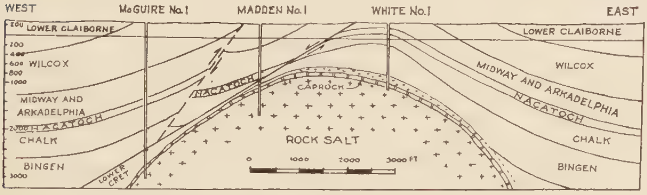
FIG. 120.—North-south section along line C–D of Fig. 119 through the salt dome area of the Isthmus of Tehuantepec. After Huntley, Stirling: A. I. M. M. E. Trans., Vol. LXIX, p. 1156, 1923.

Salt Domes of the Interior Gulf Coast Plain.—The salt domes of Texas and Louisiana are roughly divided into two groups, the interior domes and the coastal domes. In the first group 17 domes are known.

Six of these lie along the axis of the geosyncline, which is formed in eastern Texas by the Sabine uplift on the east and the Paleozoic rock areas on the west. The others are in Louisiana and lie east of the Sabine uplift. In contrast to the domes of the southern portions of Texas and Louisiana, which are commonly productive of oil, only one of the interior domes is known to contain oil in substantial amounts. This is the Boggy Creek dome in Cherokee County, Texas. The discovery of oil was made in 1927.



A. Vacherie Salt Dome.



B. Arcadia Salt Dome.

Fig. 121.—Cross-sections of the Vacherie and the Arcadia salt domes, northern Louisiana. After Spooner, W. C.: A. A. P. G. Bull., Vol. 10, pp. 228 and 245, 1926.

The interior salt domes have been found mainly through their surface manifestations; such as, saline prairies and licks, small saline lakes, saline springs or water wells, circular drainage systems around a central hill or hills containing a central prairie or lake, exposures of tilted rocks and inliers of older rocks, exposure of cap rocks, and abnormal soils. In some cases they have been identified by shallow drill holes striking old formations, cap rock, or even salt masses.

The interior salt domes are largely of the cylindrical plug type. No elongated domes are known. They vary in diameter from three-fourths of a mile to one and one-half miles. The salt bodies do not show very much increase in diameter with depth, wells off to the sides of the domes not finding salt in some cases though drilled to depths of more than 3,000 feet. Many of the salt domes of the interior have

TABLE 58.—TABLE GIVING CHARACTERISTICS OF INTERIOR SALT DOMES OF TEXAS AND LOUISIANA.*

Salt Dome	Salt Core					Cap Rock		Saline "Licks" or Lake		Wells		Geology		Amount Uplift Strata	Diameter Area Uplifted
	Found	Shallowest Known Depth Feet	Top Eroded	Diameter Miles	Mined During Civil War	Found	Depth Feet	Central	Circular around Central Hill	Deepest on Top Dome	Deepest on Side Dome	Normal Surface Formation	Oldest Formation Cropping Out	Feet	Miles
Texas															
Grand Saline	X	235	Yes	1¼	Yes	X	188	X	....	520	3,842	Wilcox	Wilcox	500	2½
Steen	X	300?	Yes	1	Yes	X	75	X	....	600?	2,630	Mt. Selman	Wilcox	500	3
Brooks	X	220	Yes	1½	Yes	X	195	X	....	429	3,193	Mt. Selman	Austin	4,300	3
Keechi	X	2,162	?	1	No	No	....	....	....	3,170	3,048	Mt. Selman	Taylor	3,500	3½
Palestine	X	122	Yes	¾	Yes	X	120?	X		700	....	Mt. Selman	Buda	5,500	4¼
Butler	X	312	?	1¼	No	?	....	X	X	1,200	1,220	Wilcox	Navarro	2,500	3½
Louisiana															
Bistineau	X	1,862	Yes	1½	Yes	X	1,420	X	....	2,305	3,245	St. Maurice	Marlbrook	1,500	4
Vacherie	X	777	No	1 × 1½	No	X	658	X	...	897	2,558	St. Maurice	Arkadelphia	1,500	3 × 4
Arcadia	X	1,400	No	1½	No	X	1,375	X	...	4,012	3,450	St. Maurice	Arkadelphia	2,350	4
Rayburn	X	115	Yes	¾	Yes	X	At surface	X	....	277	3,003	St. Maurice	Blossom	2,200?	3
King's	X	175	Yes	1	Yes	X	160	X	....	136	2,225	St. Maurice	Marlbrook	2,000	3
Price's	X	1,300?	?	¾	Yes	X	1,100?	....	X	None	?	St. Maurice	Wilcox	1,500	2
Prothero	....	....	?	1 × 1¼	No	No	....	X	....	None	None	St. Maurice	Blossom	3,000	2½
Drake's	X	900	Yes	1	Yes	X	290	X	....	2,312	1,510	St. Maurice	Wilcox	1,500	2½
Winnfield	X	999	No	1½	No	X	At surface	X	....	1,110	4,021	Cockfield	Wilcox	2,000	2½
Cedar Creek	....	....	?	1	Yes	X	801	X	....	700	3,150	Cockfield	St. Maurice	1,500	3
Coochie Brake	....	....	....	1	No	No	....	X	....	None	3,100	Cockfield	St. Maurice?	1,500	2½
Clear Lake	X	234?	?	1	No	?	......	X	..	....	3,463	Cockfield	St. Maurice	1,500?	2½
Gibsland	....	1,238	....	....	No	X	1,142	....	..	1,520	....	St. Maurice	....	1,000	2

The location of the Louisiana domes is as follows: Bistineau, secs. 35, 36, T. 18 N., R. 10 W.; Vacherie, sec. 16, T. 17 N., R. 8 W.; Arcadia, sec. 29, T. 18 N., R. 5 W.; Rayburn, sec. 31, T. 15 N., R. 5 W.; King's, secs. 34, 35, T. 15 N., R. 8 W.; Price's, sec. 30, T. 13 N., R. 4 W., and sec. 25, T. 13 N., R. 5 W.; Prothero, secs. 7, 8, 17, 18; T. 14 N., R. 6 W.; Drake, secs. 20, 21, T. 12 N., R. 5 W.; Winnfield, sec. 19, T. 11 N., R. 3 W.; Cedar Creek, secs. 30, 31, T. 11 N., R. 2 W.; Coochie Brake, sec. 6, T. 9 N., R. 4 W.; Clear Lake, secs. 28, 29, 32, 33, T. 11 N., R. 6 W.; Gibsland, sec. 15, T. 18 N., R. 7 W. (Discovered December 1925).

* After Powers, S.: A. A. P. G. Bull., Vol. 10, p. 14, 1928.

risen to within a few hundred feet of the surface. The surface of the salt in domes reached at shallow depths is horizontal and appears to have been eroded. The number of shallow depressions found above salt domes tends to indicate that solution of considerable quantities of salt has taken place in some cases.

The salt is a very pure sodium chloride but is streaked with color bandings. These are contorted and twisted so that they resemble the bandings of schists. Analyses of the salts show that the black or dark bands contain substantial amounts of calcium sulphate. While this may be the cause of the color, it may also be considered as due to interbedded organic and clay matter. Cap rocks are present above most of the salt masses. They are generally shells from a few feet in thickness up to 50 feet. At Winnfield, Louisiana, the cap rock is exposed and is apparently nearly a thousand feet in thickness. The cap rocks in some cases appear to be interfingered with sedimentary beds. The usual cap-rock material of the interior domes is limestone, but anhydrite and gypsum are prominent in some cases.

The thickness of the salt cores is not known, but a test at Arcadia stopped in salt at a depth of 4,012 feet. There seems to be sufficient evidence to indicate that the salt bodies extend down to a level underlying the Lower Cretaceous beds and that the uplift associated with the salt cores in this area affects beds of Lower Cretaceous, Upper Cretaceous, and Tertiary ages. This is indicated by the drilling into uplifted Lower Cretaceous sediments on the flanks of the domes and the identification of Lower Cretaceous fossils in conglomeratic matter in the cap rock portion of the domes.

Gulf Coast Domes.—In several of the salt domes of southern Louisiana the salt lies within a few feet of the surface. The shallowest depth at which salt has been found in Texas is at 400 feet. This occurs at Blue Ridge. In Goose Creek, Edgerly, and Orange the salt has not been reached in drilling. Yet in Edgerly oil is obtained below 3,000 feet; at Goose Creek, at 4,200; and at Orange, below 5,000. These areas are commonly grouped with the salt dome types because of the similarity of the outlines of the producing areas with those of pools where salt cores are known. At Saratoga cap rock was encountered at about 1,500 feet; but, although other wells have gone down to 2,200 feet and have drilled through about 300 feet of cap rock, the salt core does not appear to have been reached.

The domes of the Gulf Coast area vary in diameter from half a mile to two miles. The outlines are either definitely circular or have the forms of very broad ellipses. The sides are nearly vertical and the tops are in most cases flat. Like the salt of the interior domes, the salt is largely a pure sodium chloride. It contains dark to black streaks. In one instance the salt has been shown to contain potash. This was found in a core taken by the Rycade Oil Corporation in its Number 1 Gray at Markham.[1] The same test showed the presence of algae.

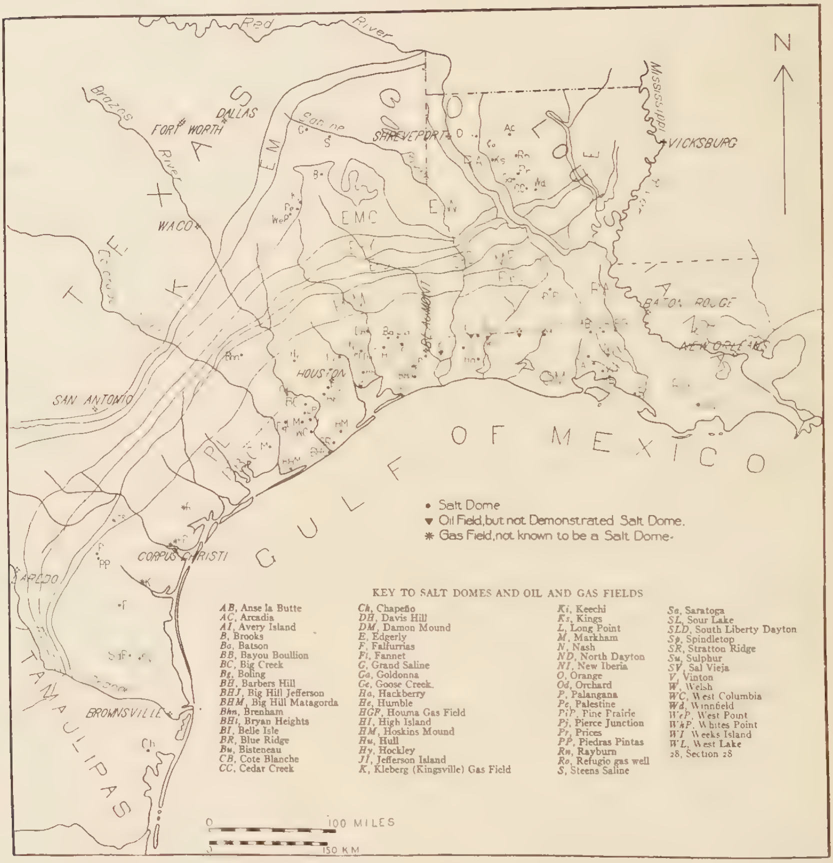


FIG. 122.—Sketch geologic map of Texas and Louisiana, showing location of the salt domes and the non-salt dome oil and gas pools of the Gulf Coast. Adapted from Barton, D. C.: A. A. P. G. Bull., Vol. 9, p. 1231, 1925.

The cap rock consists of a thimble or disc-like body of limestone.

---

[1] De Golyer, E.: A. A. P. G. Bull., Vol. 9, p. 349, 1919.

gypsum, or anhydrite. The cap rock extends down the flanks as a thin band in most cases. Generally the crystallized anhydrite composes the bulk of the cap. The limestone is usually limited to a thin layer above the main gypsum-anhydrite layer. The thickness of the cap rock as a whole varies from practically nothing to more than 1,000 feet. An average of 300 to 400 feet is usual. The cap rock of many domes shows appreciable amounts of sulphur. In a few cases the sulphur is present in sufficient quantities to make its commercial exploitation possible.

The area in which the Gulf Coast domes lie is largely covered by Recent and Pleistocene deposits. The salt domes are known to cut all of the Tertiary beds above the Claiborne group of Eocene age. The total depth of Tertiary beds is not definitely known. While their close relationship to the interior domes would indicate that the salt has a source below the Cretaceous and penetrates beds of that age, this has not been proved. The test of the Texas Company at Humble indicated that the salt must have come from a depth of more than 5,400 feet.

The salt domes of Roumania lie in areas of intense tectonic activity. Those of Germany show less marked but nevertheless definite evidences of compressional folding. In the Isthmuthian area of Mexico the same relationship between lines of folding and the alignment of the salt masses is believed to exist. In the Gulf area such relationships, if present, are not clearly indicated. The interior domes are close to areas in which major uplifts have occurred. Of these the Sabine uplift and the uplift of the Paleozoic rocks west of the Balcones fault zone have been of major importance. The salt domes of the coast lie in a belt in which the strata are practically horizontal except for the narrow belts surrounding the salt cores.

Oil in the Gulf Coast Domes.—The oil associated with the salt domes of southern Texas and Louisiana is found in three distinct sections: above the cap rock, in the cap rock, and in sands extending off to the sides or flanks of the domes themselves. Cap rock production is not of great importance in most domes but was the major source of oil in Sourlake and Batson and in the early development of Humble and Spindletop. Where the cap rock is found to yield oil, accumulation has occurred in a highly porous portion of the limestone cap. Gusher wells of large initial yield are prominent in such cases. The cap rock in some places is filled with hot sulphur water and in others proves to be dense and entirely dry. The production at Saratoga has

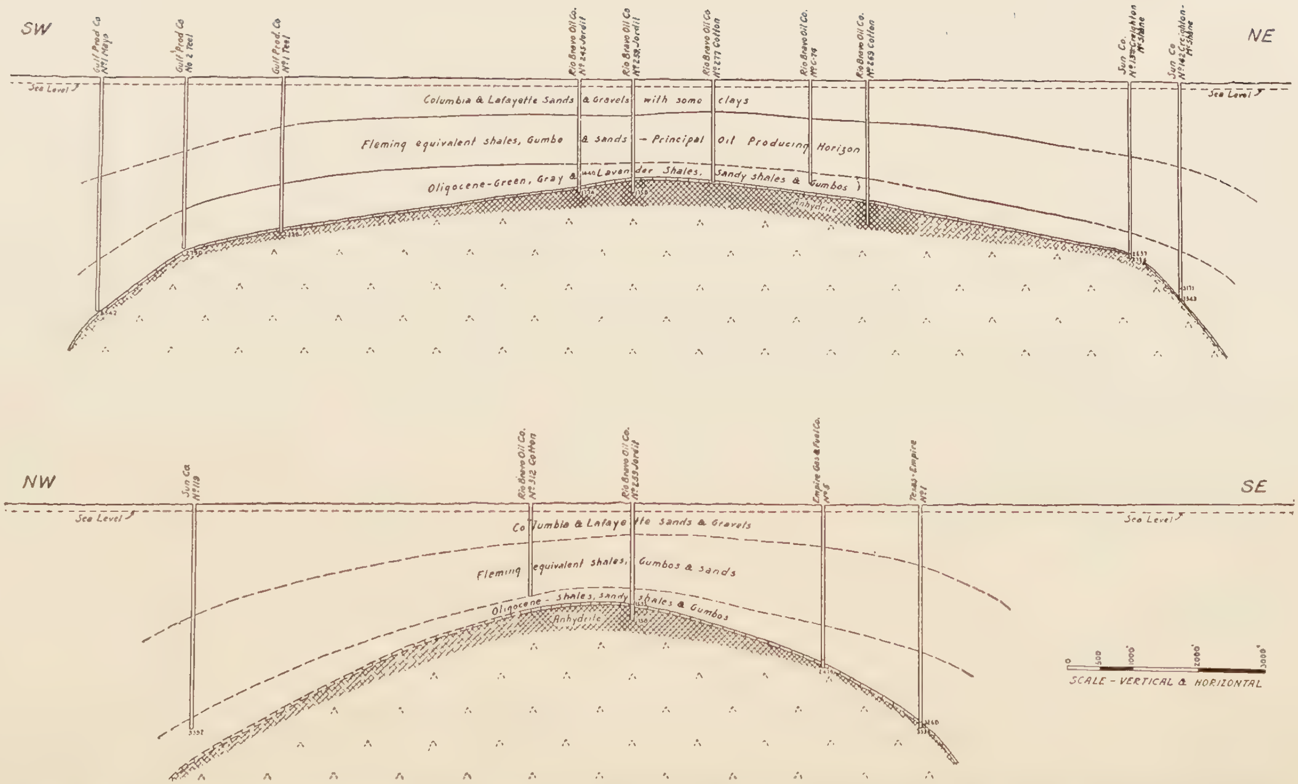

SW
NE
Gulf Prod Co Nº1 Mayo
Gulf Prod Co No 2 Teel
Gulf Prod. Co Nº1 Teel
Rio Bravo Oil Co. Nº 245 Jordil
Rio Bravo Oil Co Nº 258 Jordil
Rio Bravo Oil Co Nº 277 Cotton
Rio Bravo Oil Co. Nº C-74
Rio Bravo Oil Co. Nº 269 Cotton
Sun Co. Nº 137 Creighton McShane
Sun Co Nº 142 Creighton-McShane
Sea Level
Columbia & Lafayette Sands & Gravels with some clays
Fleming equivalent shales, Gumbo & sands - Principal Oil Producing Horizon
Oligocene-Green, Gray & Lavender Shales, Sandy shales & Gumbos
Anhydrite
NW
SE
Sun Co Nº 119
Rio Bravo Oil Co. Nº 312 Cotton
Rio Bravo Oil Co. Nº 253 Jordil
Empire Gas & Fuel Co. Nº 5
Texas-Empire Nº 1
Sea Level
Columbia & Lafayette Sands & Gravels
Fleming equivalent shales, Gumbos & sands
Oligocene - shales, sandy shales & Gumbos
Anhydrite
0
500
1000
2000
3000
SCALE - VERTICAL & HORIZONTAL

FIG. 123.—Cross-sections showing position of producing beds above the cap rock in the Saratoga oil pool. After Suman, J. R.: A. A. P. G. Bull., Vol. 9, p. 271, 1925.

come almost entirely from gently folded and apparently somewhat lenticular sands overlying the cap rock. The production of Goose Creek and Orange must, if they are ultimately proved to have salt cores, be considered as coming from similar beds above the cap rock. The deep production of Humble, Damon Mound, Hull, and the more recent developments at Spindletop have come from horizons on the flanks of the salt cores. Flank production comes from highly tilted sediments, some being nearly vertical in position.

TABLE 59.—TABLE OF SOME CHARACTERISTICS OF THE MORE IMPORTANT PRODUCING STRUCTURES OF SOUTHERN TEXAS AND LOUISIANA.

Pool.	Date of first commercial production.*	Yield to close of 1927 in barrels.*	Relation of producing horizons to salt mass.		
			Sands above cap rock.	Cap rock.	Lateral sands.
Batson	1903	33,775,000	×	×	Minor
Barber's Hill	1918	1,117,000		×	×
Big Creek	1923	2,391,000			×
Blue Ridge	1918	3,633,000	Minor		×
Boling	1925	1,922,000			×
Damon Mound	1918	6,946,000			×
Edgerly	1914	7,021,000	No salt or cap discovered.		
Goose Creek	1912	61,705,000	No salt or cap discovered.		
Hull	1918	56,890,000			×
Humble	1905	99,424,000	×	×	×
Jennings	1902	43,655,000	×		
Lockport	1924	3,607,000			×
Orange	1912	26,411,000	No salt or cap discovered.		
Pierce Junction	1921	7,345,000			×
Saratoga	1904	24,804,000	×		
Sourlake	1902	71,122,000	×	×	×
South Liberty	1925	7,820,000			×
Spindletop	1901	87,735,000	Shows	×	×
Vinton	1910	29,487,000			×
West Columbia	1918	65,691,000	Shows		×

* From U. S. Geological Survey and The Oil Weekly.

Theoretical Problems Connected with Salt Domes.—It will be readily seen that any theory which can successfully and adequately explain the form and origin of salt domes will aid materially in the search for them and in the investigation of their value as containers of oil and gas. The problems involved in the solution may be divided into three major types.

1. The question of the ultimate source of the salt.
2. The determination of the causes and manner of uplift.
3. The problem of the origin of the cap rock.

The three problems have many subdivisions. At the same time they are so intimately associated with one another that the solution of one cannot be made without reference to the other two.

Source of the Salt.—Many of the early writers on the subject of American domes considered the uplifts to be of igneous character, and therefore concluded that the salt and associated gypsum and limestone were moved upward through vents extending from below the outer shell of the earth's crust. More recent investigations have practically all postulated a source within the crustal portion of the earth. Further agreement concerning depth and geologic age of the salt is not general among geologists except with regard to the age of the salt in the German domes.

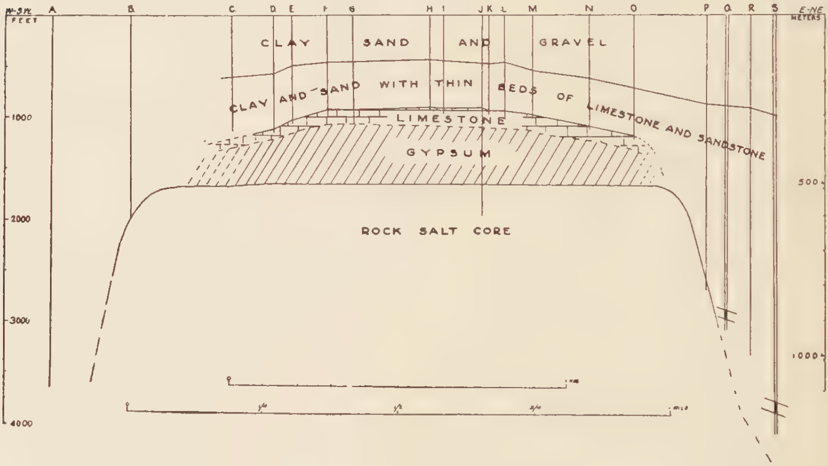


Fig. 124.—East-west section through the Spindletop salt dome, showing relation of cap rock and flank production to salt core. After Barton, D. C., and Paxson, R. B.: A. A. P. G. Bull., Vol. 9, p. 600, 1925.

In Germany the close relationship between the bedded salts, the anticlinal salt domes, and the salt stocks, leaves no question concerning the identity of their origin and therefore of the age of the salt contained. The conformity and interbedding of the salt with Permian beds definitely places them in that age.

In Roumania the salt is commonly considered to have originated in the Eocene-Oligocene or in the Early Miocene. I. P. Voitesti,[1] however, considers that the salt must have come from a much greater depth than this. He believes that the salt masses penetrate all of the

---

[1] Geology of the Salt Domes of the Carpathian Region of Roumania, A. A. P. G. Bull., Vol. 9, pp. 1165–1206, 1925.

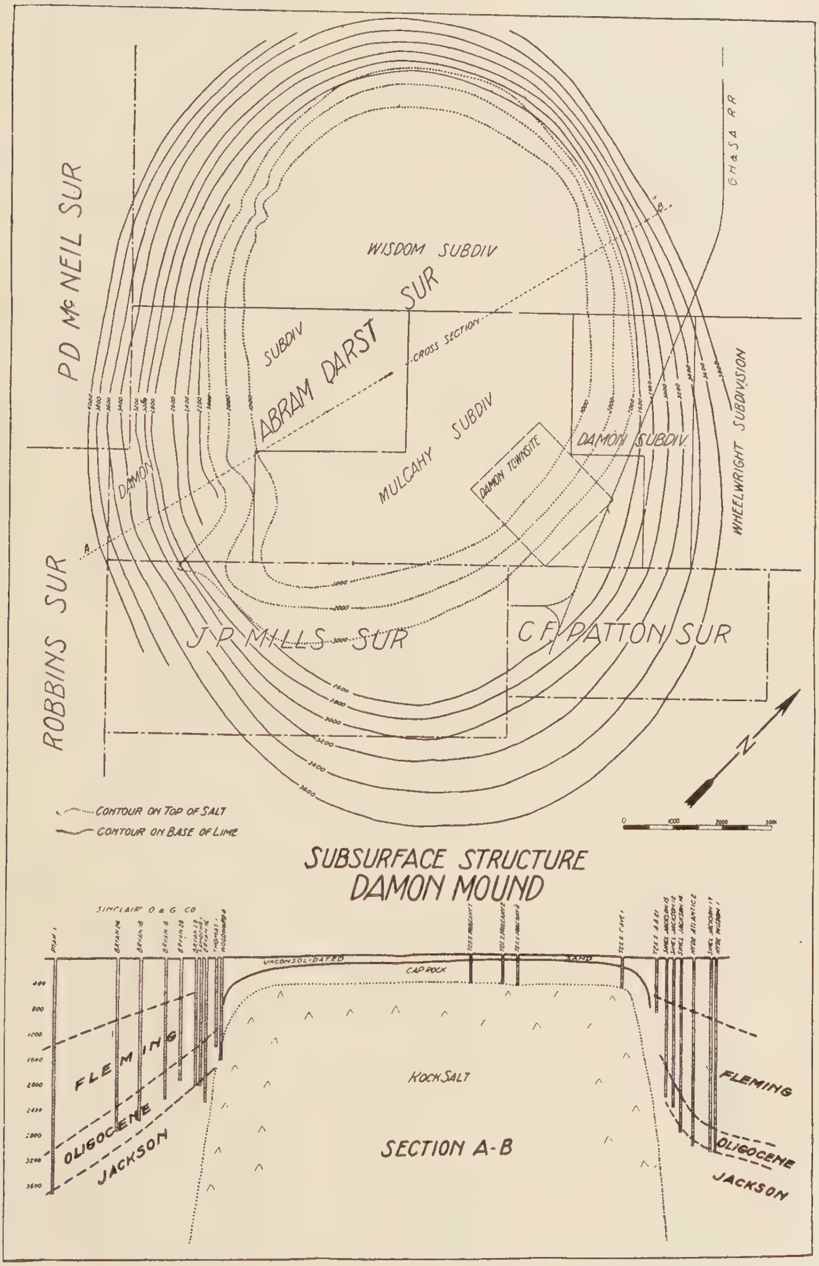


FIG. 125.—Subsurface structure and cross-section of the Damon Mound salt dome, showing position of producing wells on the flanks of the salt core. After Bevier, G. M.: A. A. P. G. Bull., Vol. 9, p. 524, 1925.

Mesozoic and Tertiary formations of the Carpathian, Sub-Carpathian, and Transylvanian areas and considers that the salt must have been introduced from a point below the Jurassic. Finally he suggests the use of a Pre-Cambrian source.

The chief evidence supporting the view of the intrusion of the salt from below the Mesozoic is the existence of brecciated material of Pre-Tertiary character above the salt masses. Some of this is considered to be of Jurassic age. This must be admitted as evidence in favor of the origin of the salt in rocks of periods previous to the Mesozoic. It does not support the Pre-Cambrian hypothesis any more than it would a hypothesis of origin in the Paleozoic. Against the hypothesis is the lack of knowledge of suitable conditions for salt deposition in the periods prior to the Miocene. On the other hand, the Miocene is known to contain only the highly domed and contorted salt masses. No bedded salts such as those of Germany have been identified. W. A. J. M. Van Waterschoot Van der Gracht[1] points out the possibility of squeezing of the entire body of bedded salts into domes and contorted bodies under the extreme pressure and stresses of Carpathian movements. Lastly, the large extent and intensity of overthrust faulting leads to the suggestion that, while the salt may have intruded Mesozoic sediments from below, the position of those sediments may be abnormal and not indicative of the original existence of salt below them. The solution of the age problem must be determined later by deeper drilling. The importance of the age in Roumania cannot be overestimated. If an origin below the Miocene is proved, the thickness of sediments having structural possibilities of containing commercial quantities of oil is greatly increased.

Less is known about the salt areas of southern Mexico than about any of the other areas discussed. The region is one of comparatively regular folding. It bears no resemblance to the highly contorted, overturn folded, and thrust faulted area of Roumania. The salt is surrounded by Tertiary rocks. Massive Cretaceous limestones have been pushed through to the surface in a number of places, and in one there is a patch of Triassic material over the salt. The Triassic should normally lie at least 6,000 feet below the surface. As there is no evidence of extreme overthrusting, it would seem that the salt must be definitely considered as having come from below the Triassic and having been uplifted more than 6,000 feet. There is no evidence to indicate that the salt source can be referred to the Permian or to any other individual period as yet.

---

[1] A. A. P. G. Bull., Vol. 9, pp. 1206–1209.

While there may be slight differences in the age of the uplifts in different areas in southern United States, there is no evidence to indicate that there is any difference in the source from which the coastal and the interior domes came. While the sediments known to be penetrated by the coastal salt reach only to the Eocene, the identification of the uplifted Lower Cretaceous beds on the flanks and conglomeratic matter on the cap rock in the interior domes would indicate that the salt in both must be conceived as either of Lower Cretaceous age or older. The possibility of a Lower Cretaceous source is supported by fragmentary evidence only. The absence of intense structural disturbances in the known Lower Cretaceous of the Gulf area leads to questioning the probability of this source. There is no definite knowledge of the existence of Jurassic and Triassic rocks in the area. The Paleozoic underlying mass is similarly unknown although its existence is firmly believed in by many.

The most important item is the knowledge that the salt is at least as old as the Lower Cretaceous. The absence of overthrust faulting definitely permits this statement. The thickness of sediments in the area close to the coast, assuming that the Lower Cretaceous is the source, is greater than the depths penetrated by drills up to the present and permits a considerable amount of further deep drilling.

Mechanics of Uplift.—Discussions of the origin of the salt masses have been going on simultaneously in the three areas in which the salt masses are of greatest importance: Germany, Roumania, and the United States. The differences in conditions under which the salt was found led naturally to differences in the nature of the explanations developed. Where crustal movements were as marked as in Germany and Roumania, compressive forces were given first importance. Where the salt occurred in practically flat areas as in the United States, theories depending upon direct uplift from below were logically developed.

Probably the greatest distinction between theories is in the question of the form of the salt during the period of its intrusion into the overlying sediments. European authorities from the beginning considered the salt as having been forced into its present condition in a plastic condition. Until 1916 practically all explanations of the American domes made use of water as a carrying agency. At present the tendency appears largely to support the idea of plastic injection.

Probably no problem in recent geology, and certainly no problem in petroleum geology, has been the subject of so much discussion as that of the origin of salt domes. The discussion of all of the theories advanced to explain the occurrence of salt domes in the Gulf Coast area alone would be beyond the possibilities of this volume. Two general ideas have been outstanding in the development of the deposition from solution theories: one, that salt domes are a type of igneous phenomena; and the other, that they have been formed by circulating artesian waters.

Hager's Igneous Intrusion Theory.—The first was supported by a number of geologists who were particularly acquainted with the early development of the area. Of the various statements made by these men, the hypothesis proposed by Lee Hager was probably the best.[1] It received wide support. The theory as outlined by him follows:

> "The movement which resulted in the great Balcones fault, or a similar movement in Later Tertiary times, extended to the rock-sheets below the present Coastal Plain, accompanied by igneous activity as in the vicinity of the fault itself. Block faults resulted, thrust up by the intrusive masses of igneous material in the form of laccoliths at great depths. Owing to the nature of the Tertiary deposits, yielding clays, marls and quicksands, the faulting proper was confined to the deep lying, indurated Lower Cretaceous and Carboniferous rocks. In the unconsolidated materials of the overlying Tertiary and Upper Cretaceous a dome-like structure resulted, due to the vertical thrust of the fault blocks pushed up by the intrusive masses in the form of laccoliths.
>
> "By contact with the molten intrusives, vast quantities of gas were generated from the reduction of metallic sulphides and the distillation of lignites and organic substances. These gases, accompanied by steam under tremendous pressure, forced their way to the surface through unconsolidated sands and clays of the overlying Tertiary material, perhaps giving rise to mud volcanoes, such as occur in many of the world's great oil fields at the present day. Heated water from great depths found vent along the same channels, carrying in solution carbonates of lime and magnesium and salt. By ebullition and evaporation these solutions became concentrated until saturation resulting, precipitation commenced forming the neck-like masses of salt, gypsum and dolomite now encountered. With the cooling of the intrusive masses and the choking of the vents, the process practically

---

[1] The Mounds of the Southern Oil Fields, E. & M. J., Vol. 78, pp. 137–139, 180–183, 1904.

ceased. A period of subsidence during which the Coastal Quaternary beds, which at present cap the mounds, were laid down, followed by a secondary movement along the old lines of weakness, resulting in the present elevation of the mounds above the surrounding prairie."

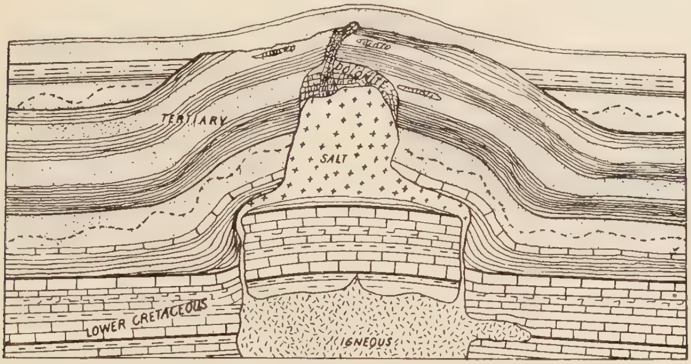


Fig. 126.—Diagram showing assumed cross-section of a typical salt dome, according to the igneous intrusion theory. After Hager, Lee: Engineering and Mining Journal, Vol. 78, p. 138, 1904. ! ec, p. 391

Hager, in advancing the theory, pointed out the weakness of the hypothesis because of the assumption of the existence of deep-seated intrusives in the area. The only immediate support for this lies in the existence of igneous rock masses in the vicinity of Austin, Texas, a point considerably west of the salt dome area. A more distant reflection has been suggested in the more abundant igneous intrusions of eastern Mexico.

Crystal Growth Theory.—The stumbling block to wide acceptance of Hager's theory or to others developed along parallel lines rested primarily in the absence of the igneous masses suggested. G. D. Harris[1] in 1907 and succeeding years formulated the artesian water circulation theory, which was until recently the most generally accepted theory of the origin of the salt domes of the southern states. It is frequently known as the theory of growing crystals since the doming of the sediments was considered to have resulted from the force exerted by the precipitation of salts from solution.

According to the theory, waters entered pervious layers of outcropping formations north of the salt dome areas. They descended to great depths in the vicinity of the Gulf Coast. Their temperature was raised accordingly; and they took into solution many salts, especially sodium chloride. As they crossed lines of weakness, they tended to move upward toward the surface. Ascending under the push of hydrostatic pressure, the waters tended to cool at the rate of 1° C. to every 90 feet of ascent. As the temperature dropped, the saturated water was compelled to give up part of its dissolved salt.

---

[1] Rock Salt, Geological Survey of Louisiana, Bull. No. 7, Report of 1907; and The Geological Occurrence of Rock Salt in Louisiana and Texas, Economic Geology, Vol. 4, pp. 12–34, 1909.

With the precipitation came crystallization of the salt. The power of growing crystals, according to G. D. Harris, is of the same order of magnitude as their crushing strengths. This he considered from tests made upon a four-inch cube to be at least 50,000 pounds and concluded that growing crystals could lift up 3,000 or 3,000 feet or even greater thicknesses of incoherent Quaternary clays and sands. The description of the formation of the salt core as given by Harris[1] is as follows:

> "At first the salt core would be a slender pencil-like cone. By rapid growth at the base, the apical angle would become greater and greater. The exact shape of the base of the cone would depend on many things, among which would be the comparative thermal conductivity of the salt core and the surrounding and subjacent materials. Crystals formed at the base of the core would give the whole mass an upward movement like a pelelith. The apex would be above the isogeotherms where salt deposition is possible; and being of very limited lateral dimensions, it would soon be dissolved by circulating underground fresh waters. However, the compacting slickensiding of the deposits about the lower main part of the core would tend to debar the close appearance of the fresh waters and yet leave a suture line for the ascension of the brine. So long as the supply of salt water lasted the salt core would continue to grow and rise. But movements along the various fault lines already depicted might at any time shut off the supply of brine. Other solutions might be forced through the channels formerly conducting salt water. We note in the domes, next in importance to rock salt, gypsum, limestone, dolomite, indurated calcareous and siliceous lenses of various shapes and dimensions. Sulphur, even, alternates with gypsum layers.
>
> "In an ordinary salt dome there should be growth not only at the bottom but also on the sides. The ascending saline solutions would vary somewhat as slight movements took place in the deep-lying beds

---

[1] Econ. Geol., Vol. 4, pp. 23–25.

below and northward from any dome-forming area. These variations would be apparent in the salt as nearly vertical streaks or layers when the mass is exposed in the huge chambers of salt mines. These streaks, then, may be regarded as of exogeneous growth rather than bedding planes highly inclined."

The wide acceptance of the salt crystal growth theory of Harris may have been partly due to the lack of a substitute for it. Certainly within the last few years since the development of the plastic intrusion theories, it has been the object of intense criticism. The objections to the theory are largely quantitative. The first is the extreme size of the salt masses themselves. Widths up to a mile and a half and depths of more than five thousand feet are now known. The circulation of brine necessary for such a deposit must have been continuous over a long period of time. There is no evidence of such circulation having taken place. Secondly, the force attributed to growing crystals has not been proved to be operative on so large a scale as is called for.

Plastic Flow Theory.—The third theory and the one now most generally accepted even in the United States is that of plastic flow. The exact cause of the flow is open to discussion but is generally attributed to some form of pressure. The salt masses are, according to this theory, to be considered solely as extreme types of folds in incompetent strata. The degree of thickening of the salt beds must be considered as a direct reflection of the intensity of the forces applied. The form of the resulting dome whether ridge-like or quaquaversal must, like the form of the ordinary anticline, be determined by the conditions in the shear zones and competent beds and by the direction of the application of the pressure. In other words, the outlines of the salt masses in any particular area are a direct reflection of the tectonic conditions of that area. The form normal to one area is not necessarily found in the other. Within the one section resulting forms may differ because of differences in the manner in which the different forces have been applied.

Broadly considered, the movement of the salt must be due to either isostatic or orogenic conditions. Uplift because of isostatic differences implies that the salt has been squeezed upward through lines of weakness due to the greater density of the overlying sediments. The specific gravity of salt is about 2.15. The density of loose surface beds is between 1.4 and 1.8 in the Gulf area. The average density of the minerals composing the rocks and soils is about 2.6. While it is apparent that the specific gravity of a deeply buried sediment increases materially with compacting and tends to approach the average of its component minerals, there is no reason to believe that the weight of a column of such sediments will be materially greater than that of a similar column of salt. It does not appear that the force suggested is adequate to overcome friction, which would tend to prevent movement within the salt mass and along the contact between the salt and the adjacent sediments. Where unfractured sediments rest on top of the salt mass in domal arrangement, their dead weight must also be considered as a neutralizing agency. The use of the isostatic idea alone seems to have but little support at the present time.

Orogenic forces are generally considered as resulting in direct lateral thrusts. Where the axial lines of the salt dome ridges are as closely related to the adjacent mountain ridges as they are in the outer arc of the Carpathians, there is no reason to doubt the application of lateral thrust. The intensity of the overthrusts that accompanied this mountain building lends further support to this view. Similarly there is close relationship indicated by the alignment of the axes of the salt dome ridges of the Magdeburg-Halberstadt Basin with the folds of the adjacent old mountain masses. In some cases the axes of the domes show evidence of folding movements from two directions, that is, Heroynian or Saxon folding, and Rhenish folding. The circular form of dome is more common in the domes of the North German plain than it is toward the mountain areas and sections of most intense folds.

Many Mexican domes are elongated in a direction parallel to the folding in that area. There were apparently two systems of folding in southern Mexico that were nearly at right angles to each other and have caused the development of cross-axial or quaquaversal domes.

In the salt dome areas of Texas and Louisiana, there is evidence of some alignment of domes. The lines are not distinct in the interior areas except possibly in northeastern Texas where the alignment seems to be parallel to the strike of the Balcones fault system. In the southeastern portion of Texas there is a very definite tendency for the domes to lie in lines running NNE to SSW bending somewhat to the southwest at their southern extremities. In southwestern Texas the domes lie along a NNW–SSE line. In southern Louisiana there is a NW–SE line and also a well-marked east and west line of domes.

The Gulf domes, in all of the cases where the drill has penetrated sufficiently to outline the form, show a marked circular form. This is to be expected if the domes are the result of lateral compression from different directions at right angles to each other. However, the strata of the Gulf area show no evidence of such compression. The salt outlines are as a matter of fact more regular than those in other areas in which cross-folding has taken place. The application of the theory of lateral compression to the uplift of the salt in this area is difficult to understand. Certainly the normal faults, which characterize the Balcones and adjacent fault zones and probably accompanied the Sabine and related uplifts, were not accompanied by extreme compressive action.

Unless reliance be placed upon the volcanic or the growing salt crystal theories, the postulation of a different type of compressive force than that of Roumania, the Magdeburg-Halberstadt Basin of Germany, and even the Isthmuthian area of Mexico, seems imperative. If the plastic flow theory is to be retained, the difference in result must be considered as due to conditions in the underlying basement rocks and to application of the forces to those rather than the overlying rocks. The author feels that the force acting upon the salt beds and inducing their upward movement will prove to be a combination of isostatic pressures tending to cause lateral flowage toward areas of lower pressure, plus movement within the deeply buried competent beds and within the shear zone along old lines of weakness. Discussion of these points is wholly without means of proof at the present time and hardly within the scope of this text.

Period of Folding and Uplift in Gulf Area.—The actual age of the development of the salt domes is indicated as being comparatively recent in the Gulf area. In any case they must be considered as recent as the Quaternary beds, which they pierce. E. De Golyer[1] suggests that the movement of the salt has been intermittent rather than continuous and states that there is some evidence that younger and smaller salt cores have sprung from older domes in which equilibrium had been established. The progress upward he conceives as having been retarded from time to time by particularly resistant strata.

The youth of the strata penetrated in the other salt dome areas discussed suggests that they are also of comparatively recent development.

---

[1] A. A. P. G. Bull., Vol. 9, p. 866, 1925.

Salt Dome Cap Rocks.—The variations in the character of the material forming cap rocks, together with the absence of such matter in some domes and great thicknesses in others, make it a point of speculation. The theories of explanation of the origin of cap rocks may be considered as of four types:

1. The cap rock is residual—a remnant left behind after solution of the salt.
2. It is an unaltered sediment pushed up ahead of the rising salt core.
3. It is a sediment that has been pushed up ahead of the rising core, which has been altered by circulating waters.
4. It is a secondary deposit resulting from reactions in vadose waters and saline waters adjacent to the salt masses.

The first of the theories was developed largely as a result of studies in German salt domes. These salt masses contain large amounts of anhydrite intimately associated with the salt. The anhydrite may be traced as beds in the salt. Anhydrite caps above the German salt cores are extremely irregular in thickness and extend for some distance down the sides. They are of irregular texture also.

The absence of anhydrite and gypsum in the salt is commonly suggested as against the application of the theory of a residual cap to the Gulf Coast domes. While it is generally considered that the anhydrite content is small and the amount of leaching required to produce the great thicknesses of anhydrite known in some domes prohibitive, there is little definite knowledge about the occurrence of anhydrite in the salt mass itself. Thicknesses of 1,000 feet of cap rock reported in several American domes indicate a degree of leaching which seems improbable. While in some places the high porosity of the upper surface of the cap warrants the suggestion of leaching, most American caps are dense. The general absence of cap rock on the sides of the domes is difficult to explain by this theory as those areas are the most logical ones for the circulating waters to reach after the tops have been covered by dense anhydrite.

While the theory of residual origin is not entirely satisfactory, such origin must be considered as having contributed to the formation of the caps of American domes. The occurrence of surface depressions with saline waters above a number of salt domes is direct evidence that such solution is going on today. If the intermittent development of domes be admitted, the possibility of intermittent leaching during different stages in their development must also be recognized. Such leaching may have been caused by deep waters or have been the result of infiltration of surface waters at different stages. The extreme thinness and absence of cap rock on the sides may indicate that the cap material, which was formed there, has been left behind in movements of later date. The absence of openings may similarly be attributed to settling and compression during such uplifts.

The theory that the anhydrite and the limestone above it are upthrust masses of original sedimentary rocks has been developed to explain conditions in the United States. The idea of the cap as the "mass de resistance" pushed up by the salt below seems to have appealed to many. The shearing tendency of such material is considered as in keeping with the steep sides of the cap rock above the coastal domes. Further support is considered by some to be given by the lack of definiteness of the contact between salt and cap rock indicated by many logs.

Again the great thickness of the anhydrite must be raised as an objection to the sedimentary origin idea. It is true that thicknesses even greater than 1,000 feet have been measured in Permian anhydrite-gypsum beds. However, it would seem probable that the anhydrite mass, if pushed up through such thicknesses as appear to have been penetrated, would have been subject to shearing and thinning in the same way as the sediments that were displaced. This objection may be met in some cases by the suggestion that the salt uplift occurred at the same time as deposition was going on above on the surface and that the weight actually overlying the cap rock was not extreme at any time.

Some have considered the cap rock as the product of the alteration of sedimentary rocks that were being forced upward by the waters and other substances they met. This type of origin usually postulates an original cap of limestone and calls for the alteration of that limestone into anhydrite and gypsum through the agency of sulphuretted waters. Closely allied to this are the several theories that attempt to explain the presence of sulphur in the cap rocks of some of the domes by the action of carbonaceous matter upon sulphur-containing compounds, particularly the calcium sulphates. That some reactions of this nature have taken place can hardly be doubted. Those which might yield sulphur under the conditions existing in such areas as the Gulf Coast are not clearly understood. Those which attempt to ex-

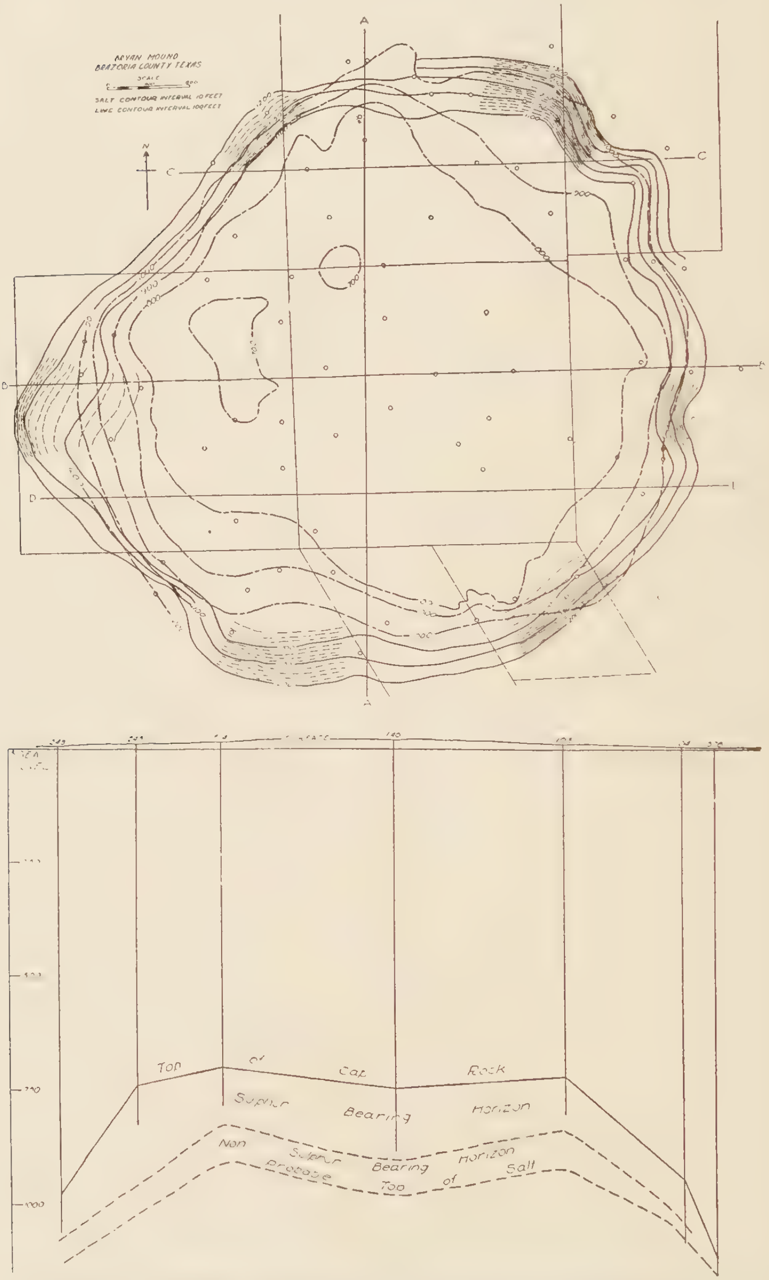


FIG. 127.—Topography of the top of the cap rock and the top of the salt in the Bryan Heights salt dome. Cross-section showing position of sulphur and relation to non-sulphur bearing portion of cap. After Kennedy, W.: A. A. P. G. Bull., Vol. 9, pp. 617–618, 1925.

plain the origin of anhydrite by alteration of limestone are subject to the objection that the existence of sulphuretted waters to the amount necessary is unproved. There is some question as to the possibility of the chemical reaction, upon which the theory is based, occurring under the conditions existing in the area.

The last of the theories considers the cap rock to be strictly a secondary deposit, a product formed by precipitation from solution. The cause of precipitation may vary. In some instances it may be considered as being due to reactions between the waters containing the cap rock materials and waters of a different origin. In others it may be due to change in temperature. It is possible to consider the cap as a deposit produced by replacement of less soluble material in the solution by more soluble material taken up from the salt core itself. The theory has much to recommend it. However, it has been noted that waters in the Gulf Coast area are generally low in sulphates. The clear-cut limits of the cap rock masses and the absence of such matter along the flanks of the salt cores and in the rocks adjacent to the salt domes of the Gulf Coast area tend to discredit the theory.

The theories of secondary deposition of cap rock material were naturally essential parts of the theories that attempted to explain the origin of the domes themselves by solutional activity. Those which utilized original sedimentary beds were allied to the theories of plastic injection of the salt. Even with the marked ascendency of the plastic flow theories, it is not possible entirely to abandon the theories that call for secondary deposition of cap rock material. The gypsum may be considered as an alteration product of anhydrite in most cases. Whether the same can be said of the sulphur and the calcite is open to question. The large number of the factors that may have had some bearing upon the result makes it impossible to make any generalizations at this time.

Conclusions.—Despite the extreme importance of the porous rocks associated with salt cores as sources of oil and the large amount of consideration given to the origin of such bodies, our knowledge of the conditions that have caused their development is extremely limited. It is not possible to make absolute statements about the origin of cap rocks even in Germany where such bodies have been penetrated by mine shafts. In Roumania, while the close relationship between dynamic movements and the development of salt cores is evident, there is no general agreement concerning the age and depth of the original source horizons. Despite the general acceptance of the theory of plastic flow as the explanation of the origin of the salt domes of the Gulf Coast plains, much remains that is difficult to reconcile with observed conditions. Depths of more than 5,000 feet have been reached by the drill in a number of places without indication of change in conditions from those observed at shallow depths. The absence of definite structural lines and the lack of knowledge of the character of the source beds and the underlying basement rocks make the study most difficult.

Despite the lack of knowledge of the origin of the domes themselves, their importance in causing the accumulation of oil and gas is fully recognized. The search for the surface phenomena that indicate their presence has added materially to the number of producing areas in the Coastal States, in Roumania, and in southern Mexico. In Texas and Louisiana, the presence of deeply buried domes has been indicated by geophysical methods of exploration whose use depended upon the differences between the physical properties of the domal material and the surrounding sediments.

SELECTED BIBLIOGRAPHY ON SALT CORE STRUCTURES WITH PARTICULAR REFERENCE TO THOSE OF TEXAS AND LOUISIANA.

The literature on salt dome structures is most voluminous both in the United States and in Europe. The American reader is naturally most interested in those discussions which deal with conditions in southern Texas and Louisiana. These are divisible into two distinct groups. The first consists of the series of papers written during the period following the discovery of Spindletop in 1901 and ending with the wide acceptance of the theories of Harris in 1910. The descriptions contained in this group of papers are largely restricted to discussion of domes that lie close to the surface and producing horizons above or in the cap rock portions. The theoretical papers are devoted mainly to theories utilizing deposition from solution as the explanation of the growth of the salt masses. The more important papers of this period include the following:

1. Fenneman, N. M., Oil fields of the Texas-Louisiana Gulf Coastal Plain, U. S. G. S., Bull. 282, 1906.
2. Hager, Lee, The Mounds of the Southern Oil Fields, E. & M. J., Vol. 78, pp. 137–139 and 180–183, 1904.
3. Harris, G. D., Rock Salt, Geol. Sur. of La., Bull. No. 7, 1907.
4. Harris, G. D., The Geological Occurrence of Rock Salt in Louisiana and Texas, Econ. Geol., Vol. 4, pp. 12–34, 1909.
5. Harris, G. D., Oil and Gas in Louisiana, with a brief Summary of their Occurrence in Adjacent States, U. S. G. S. Bull. 429, 1910.

6. Hayes, C. W., and Kennedy, W., Oil Fields of the Texas-Louisiana Gulf Coastal Plain, U. S. G. S. Bull. 212, 1903.

The second group of papers may be said to begin with the discovery of production on the flanks of the Humble salt dome in 1914. The depth of the formations affected by the uplifts accompanying the salt bodies and the size of the salt cores were more fully realized as development work proceeded. Marked improvements in drilling equipment and technic and increased knowledge of fundamental geologic conditions brought an abundance of additional information and greater ability to organize data. Where the earlier writers had been inclined to consider the conditions in the Gulf states as distinct from those in any other section of the world, investigators of this period sought the solution of their problems in the salt structures of Europe and other areas. The early papers by Van der Gracht and Rogers were followed by more complete studies by a number of others. The wide discussion of the problem reached its culmination in symposium conducted by the American Association of Petroleum Geologists. The papers presented were published in the Bulletins of the Association during 1925 and 1926, and later, as a single volume called "Geology of the Salt Dome Oil Fields." Most of the papers are limited to discussion of individual pools. Some are of a more comprehensive character and may be considered as excellent summaries of our knowledge about salt structures. These together with some of the earlier papers of this period, are listed below:

1. Barton, D. C., The American Salt-Dome Problem in the Light of Roumanian and German Salt Domes, A. A. P. G. Bull., Vol. 9, pp. 1227–1268, 1925.
2. Barton, D. C., The Salt Domes of South Texas, A. A. P. G. Bull., Vol. 9, pp. 536–589, 1925.
3. De Golyer, E., Origin of North American Salt Domes, A. A. P. G. Bull., Vol. 9, pp. 831–874, 1925.
4. Goldman, M. I., Petrography of Salt Dome Cap Rock, A. A. P. G. Bull., Vol. 9, pp. 42–78, 1925.
5. Huntley, Stirling, Oil Development on the Isthmus of Tehuantepec, A. I. M. M. E. Trans., Vol. LXIX, pp. 1150–1166, 1923.
6. Matteson, W. G., Secondary Intrusive Origin of the Gulf Coastal Salt Domes, A. I. M. M. E. Trans., Vol. LXV, pp. 295–334, 1921.
7. Powers, S., Interior Salt Domes of Texas, A. A. P. G. Bull., Vol. 10, pp. 1–60, 1926.
8. Rogers, G. S., Intrusive Origin of Gulf Coastal Salt Domes, Econ. Geol., Vol. 13, pp. 447–485, 1918.
9. Spooner, W. C., Interior Salt Domes of Louisiana, A. A. P. G. Bull., Vol. 10, pp. 217–292, 1926.
10. Stille, Hans, The Upthrust of the Salt Masses of Germany, A. A. P. G. Bull., Vol. 9, pp. 417–441, 1925.
11. Van der Gracht, W. A. I. M. V. W., The Saline Domes of Northwestern Europe, Southwestern Association of Pet. Geol. Bull., Vol. 1, pp. 85–92, 1917.
12. Van der Gracht, W. A. I. M. V. W., The Structure of the Salt Domes of Northwest Europe as Revealed in Salt Mines, A. A. P. G. Bull., Vol. 9, pp. 326–330, 1925.
13. Voitesti, I. P., Geology of the Salt Domes in the Carpathian Region of Roumania, A. A. P. G. Bull., Vol. 9, pp. 1165–1206, 1925.

CHAPTER XVII.

ACCUMULATIONS CONTROLLED BY SEVERAL FACTORS.

In the previous chapters the author has tried as much as possible to restrict himself to illustrations in which the accumulation was dominated by a single causal factor. It was not possible to give examples in which there was no modification of the action of this one factor by others of minor importance. In all of those cited, he believes, however, that the secondary factors have been of such subordinate importance as to warrant the belief that they have not materially altered the manner of accumulation. In the accumulations now to be discussed, the secondary factors are of material importance. In some, several factors have contributed so largely to the accumulation and retention of the oil and gas that it is difficult to consider that any one of them has been of greater importance than the others.

Variations in porosity in oil containers have been referred to as causes of accumulation in monoclinal and even synclinal areas. As the oil-yielding beds of folded and faulted structures were produced under the same general conditions, it is logical to expect that sands contained in such areas may vary in porosity also. In fact, the greater tendency for circulation of waters would suggest that even greater variations might be expected.

Simultaneous Sedimentation and Folding.—In the large fold other factors also enter. The duration of the period of folding is frequently great even though fairly continuous. Folding is commonly initiated before the ending of the period of sedimentation. This may result in the erosion of the higher and emergent parts of the fold while deposition is still active in other portions. Thus horizons originally continuous over the whole fold may be partly removed. The deposition of lenticular sands covering portions of the structure may be expected. This type of body is especially likely to be deposited on the flanks of the larger anticlines and upon the lower portions of the plunging anticline. Irregularities in settling may well be expected to occur because of the differences in the nature of the deposits laid down upon different parts of the partly arched fold. Similarly the differences in the thickness of the deposits upon the top of the growing fold and upon the flanks tend to cause differences in the amount of settling.

Variations in Competency.—Such variations would not be expected in areas in which the period of folding was not initiated until after that of sedimentation had ended. Even in these some variations in sand bodies may be expected. Where the sand or sandstone is the least competent of the beds being folded, its thickness may be expected to vary so as to conform with the positions taken by the more competent beds above and below it. This is probable where sandstones are found interbedded with massive limestones. It is less likely to occur in areas in which the less competent shales and clays are present.

Even where folding is accomplished in a period of short duration after the close of sedimentation, the intensity of the forces active at the different stratigraphic levels cannot be expected to be the same. If the folding resulted from the application of a horizontal thrust to a series of competent beds that overlaid incompetent ones, folds whose intensity decreased with depth might be expected. Such folds may occur, but in the great majority of cases the competent beds underlie the incompetent, and the intensity of the fold increases with the depth. In beds of as low competency as clays the vertical movement rapidly dies out in intergranular adjustments. In beds of somewhat greater competency, such as sandstones, stresses may be built up until the strength of the rock is exceeded. Fracturing is apt to occur where the static pressure of the overlying deposits is not too great. In areas of direct uplift, this means the development of normal gravity faults. Compression faults may result from horizontal thrusts. In cases of folding produced by torsional forces, faults of both the tension or reverse and the normal types may occur.

Vertical Range of Faults.—Such faults are usually of minor size and are located so as to have very little importance either in the accumulation or retention of oil by the folds upon which they occur. Others are of larger size and extend down to the beds in which the oil is contained. Their positions make them of major importance in the determination of the manner of accumulation and retention.

It is frequently assumed that faults die out with depth. This is probably true of the simple gravity types. In many cases, faults indicate the presence of folds in the underlying more competent beds; in others they reflect only adjustments in incompetent beds resulting from settling and have no downward reflection. The first may be said of the majority of the reverse types also. Many faults continue downward beyond the limits penetrated by the drill without diminution. Some tend to increase in intensity. The last quality is particularly noticeable in those faults which are considered to reflect movements in the underlying shear zone.

The development of these major faults, like the development of the large anticline is an intermittent and probably long drawn out process. The distribution of the oil and gas adjacent to them is modified by erosion, deposition, and other factors, just as in the anticlinal fold.

The major fault starts in the shear zone. It remains primarily a straight-line movement only as long as the weight of the overburden and the character of the rocks make that type of movement the easiest. Under some conditions it may extend through to the surface. This is frequently the case in areas of crystalline rocks. It is less common in areas where they are covered by thick bodies of sediments. Here plasticity tends to convert part or all of the straight-line movement into folding. Intergranular adjustments tend to reduce the amount of the movement. Actual fracturing may not occur until the sediments have been highly contorted and the bulk of the straight-line movement disappears far below the surface. In some cases it may give rise to single long folds. In others a series of closely related en échelon anticlinal folds or domes may result. This may be expected where there is considerable horizontal movement parallel to the strike of the fault in the underlying rocks.

In the upper horizons the structure may be altered further by the development of faults resulting from the stresses developed in easily fractured rocks such as sandstones. Such faults are most likely to occur close to the surface where confining pressures are small and tend to decrease in importance with depth. They reflect the folding and the deep fault movement beneath them, but they can only be considered as shallow manifestations of that movement. The exact character of result in any area will differ from that in every other area because of the differences in the character and relative importance of the several forces acting.

In the chapter on fault-line accumulation, the folds in which the actual production was obtained were considered as merely parts of the faulting. In every case discussed a portion of the straight-line movement was evident at the surface and had been of major importance in the accumulation of the oil and gas. In Chapter XII Long

Beach and Dominguez were discussed as if they were isolated structures. This is not strictly true. They lie upon a line of uplift known as the Inglewood uplift or fault. Along this are located the important pools and individual structures known as: Newport, Huntington Beach, Seal Beach, Long Beach, Dominguez, Athens-Rosecrans, Inglewood, and Beverly. Their alignment leaves little doubt that they were produced by horizontal movements along a deep-seated fault or shear plane in the deeply buried basement rocks. The action in the shear zone was probably not very different from that along the Whittier fault, a short distance to the east. The differences in structure resulting can be traced to the great thickness of the plastic incompetent sediments above the hard rock surface.

Despite the great depth of some of the producing horizons in the pools along the Inglewood fault, the domed or anticlinal form of its uplifted areas seems to continue. This is similar to conditions observed in other areas. Yet there can be no doubt that many of our producing folds change to major faults at lower depths. The few examples that might be cited of such conditions occurring within the zone penetrated by the drill are of such complex nature that their use here would be open to the criticism that data available warrant other interpretations as well.

Burial of Structures.—The structure formed by folding or faulting during one period of the earth's history may be buried beneath a covering of sediments in a later period. If erosion tends to level the area prior to the subsequent deposition, the horizontally placed beds of the later period give no indication of the underlying structure. Such structures have been called buried structures. Their origin is easily understood, but their presence is impossible of determination prior to their discovery by the drill.

Where the period of erosion is brief and base leveling does not occur prior to the second period of sedimentation, the later deposits may be laid down upon a surface whose topographic form reflects its geologic structure. The sediments of the second period of deposition will be thin over the upfolded areas and thick in the basins. Yet the briefness of the period of deposition or the greater compacting of the deposits in the basins may tend to preserve a faint reflection of the underlying structure. Such a structure cannot be called a buried one as long as any reflection remains. To this type it would seem advisable to apply the term "covered structure."

The erosion of folded and faulted areas frequently results in the rapid wearing down of those areas that had been elevated most by dynamic agencies. The irregular topographic surface bears no relation to the geologic structure of the rocks that underlie it. Deposition in such areas will follow the same lines as have been indicated for the case previous. The form of the surface beds after compacting will be similar to those above the covered structure. Yet they do not indicate underlying structural conditions at all. The topographic high spots that lie below their slight arches may well be called "covered hills."

Where the thickness of the covering completely obscures the underlying conditions regardless of their topographic form at the time of deposition, the terms "buried structure" or "buried hill" may be applied as the conditions warrant.

Revival of Dynamic Activity.—It is seldom that a period of long-continued deposition is followed by uplift that is not accompanied by some folding or even faulting. The forces causing such action act mainly through the underlying more competent rocks. Unless applied from entirely different directions than the forces that caused the folding in the underlying beds prior to their erosion, the second group of forces may be expected to act along much the same lines as the first. Thus the second period of folding or faulting may be expected to intensify the folds or faults in the rocks below the unconformity, while definite and similar structural forms are being created in the upper rocks. The structure visible at the surface following such action is true structure. Yet it does not represent the conditions in the horizons below the unconformity. It cannot be considered as the upper portion of a structure whose intensity increases regularly with depth or with approach to a given competent bed as in concentric folding. The author suggests the use of the term "revived structure" in such cases.

Further complications to the problem are introduced by the fact that horizontal forces may be applied through a hardened and possibly partly metamorphosed or crystalline base along lines other than those by which the original sediments were acted upon. It is conceivable that they might result in the uplift of a covered or buried hill whose original structure was synclinal. Direct uplift of massive igneous cored hills has undoubtedly occurred in several areas.

Where the rocks below the unconformity are crystalline or of such low porosity as to be incapable of containing commercially recoverable amounts of oil, their structural form is not of great moment. If porous horizons do occur, their attitude and extent are of major importance. Ability to distinguish between the hill and the true structure may not only assist in the development work of the individual section but be of material value in the determination of the ultimate source of the oil and of the manner of conducting operations in adjacent areas.

Accumulations at Unconformities.—The contacts between older and the younger rocks present most difficult problems to the geologist. The porous erosion surface is irregular in outline and character from the very nature of its origin. It cannot be considered as a distinct stratigraphic horizon, yet it may be folded and faulted in much the same way as such a bed would be. If continuous, it offers a passage to the oil and gas contained in the formations with which it is in contact. It permits accumulation in its own porous openings and encourages the movement of oil and gas from one stratigraphic level to another. In some cases it encourages movement from source beds on one side of the unconformity to porous containers on the other. If spotty in distribution, it may cause accumulations at points not favored by the general structure.

Before the peaks of older surfaces are covered by sediments, a number of lensing or abruptly terminating sand bodies may be laid down at their sides. Some may be deposited even after complete covering because of the sloping nature of the surfaces resulting from compacting of the sediments laid down in the basins adjacent to the emergent areas. Above the highest points of the old surfaces, there should be very little deposition prior to filling of the basins. After that, continuous beds may be anticipated. In these, accumulation should follow the structural outline given by later dynamic action. Yet it must be remembered that even in these, factors such as unequal erosion or sedimentation, which are active in modifying accumulation in the simpler types of folded and faulted structures, will be present.

Order of Discussion.—The large number of factors which modify accumulation to some degree in the majority of the world's major areas makes it difficult to group these sections in a logical manner. Where more than one modifying factor has been active, exact grouping becomes impractical. Therefore, no attempt will be made further to divide the different types of structures that come under the general heading of buried and revived types. The discussion of these complex structures will be left until last, the comparatively simple types in which accumulations in folded areas have been altered by porosity variations or faulting being discussed first.

Ranger Area, North Texas.[1]—The productive horizons in the lower part of the Pennsylvanian on the Bend Arch of northern Texas were discovered in 1917. The area was characterized by wells of large flush production of high quality oil. As the discovery came at a time when the demand for oil was great, the area was rapidly developed. Among the prominent producing areas was the Ranger district. While conditions in other portions of the Bend Arch are not entirely the same, this section may be considered as generally representative.

The surface rocks of the Bend Arch are either of Lower Cretaceous or Pennsylvanian age. The latter predominate. The producing horizons of greatest importance are those in the Marble Falls limestone of the Bend series. The Smithwick shales and the Strawn formation also contain productive beds. Frank Reeves lists nine distinct producing sands. Their position with respect to the top of the Black lime in the Marble Falls limestone is as follows:

Pays in the Strawn formation:			
Ray Sand	1,850 to	1,970	feet above.
Scott Sand	1,600 to	1,850	feet above.
Harris Sand	1,250 to	1,640	feet above.
Pay sand in the Smithwick shale:			
"Smithwick lime"		300	feet above.
Pay sands in the Marble Falls limestone:			
Bulsford Sand	75 to	160	feet above.
Top of Black lime	—	—	
Base of Black lime	80 to	130	feet below.
McClesky Sand	170 to	230	feet below.
Lower part of the Marble Falls limestone	350 to	475	feet below.

The bulk of the production in the Ranger area comes from the Marble Falls limestone. The Strawn formation wells are generally small and the pools of limited extent. The Smithwick shale production is believed to come from cavities in a thin, moderately porous limestone. While of major importance in the pools of Stephens County, adjacent to this area, it is not of importance here. The McClesky sandstone is the chief producing horizon in the Marble Falls at Ranger. It is apparently a pure sandstone. In this it differs from the other "sands" of the formation, which are sandy limestones or shales.

---

[1] Reeves, Frank: Geology of the Ranger Oil Field, Texas, U. S. G. S. Bull., No. 736, pp. 111–170, 1923.

The study of the relation of productivity of the wells to structure is made difficult by the lenticularity and changing porosity of the beds. In the shallow sands of the Strawn, these conditions are fully as important as structural considerations. In the deep horizons, the position of the porous lime sands is subject to variation. The McClesky is the most continuous of the productive horizons present. Yet it varies from a thickness of 50 feet down to nothing. Where less than 20 feet in thickness, it is usually too fine grained or too argillaceous or calcareous to yield oil. The thicker areas, that is, those in which the sand is from 30 to 50 feet thick, are usually composed of grains of larger diameter and have a higher effective porosity.

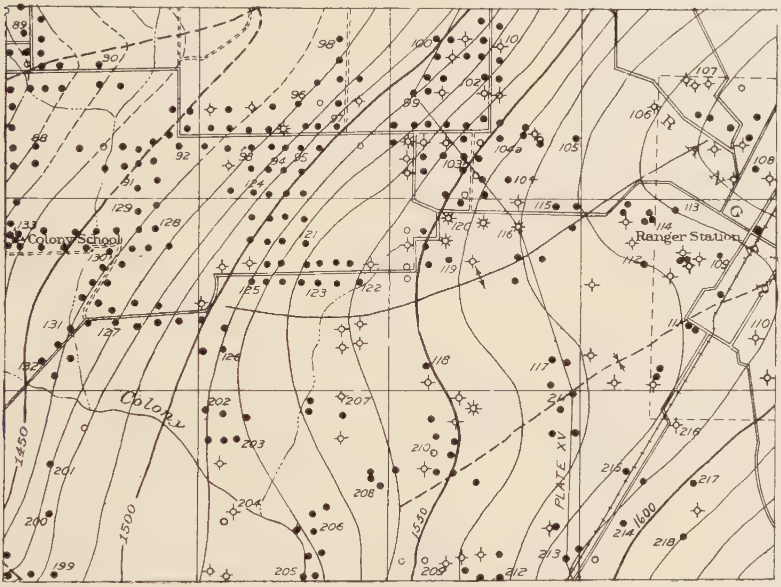


FIG. 128.—Map of a portion of the West Ranger area, Texas. Structure on outcropping beds. After Reeves, Frank: U. S. G. S. Bull. 736, Plate XVII, 1922.

As the top of the "Black lime" forms a prominent key horizon throughout the district, subsurface maps are usually drawn upon it rather than upon the individual producing horizons. The subsurface maps drawn in this way show a definite relationship between areas of production and anticlinal folds. The relationship is modified in almost every area by sand conditions.

The element of uncertainty caused by more or less irregular variations in sand conditions is further added to by the existence of a marked unconformity between the Bend series and the overlying Strawn formation. In the deep horizons of the former, there are very pronounced anticlines, plunging anticlines, and synclinal basins. The strata show uplifts of 80 to 100 feet and dips ranging up to 250 feet to the mile.

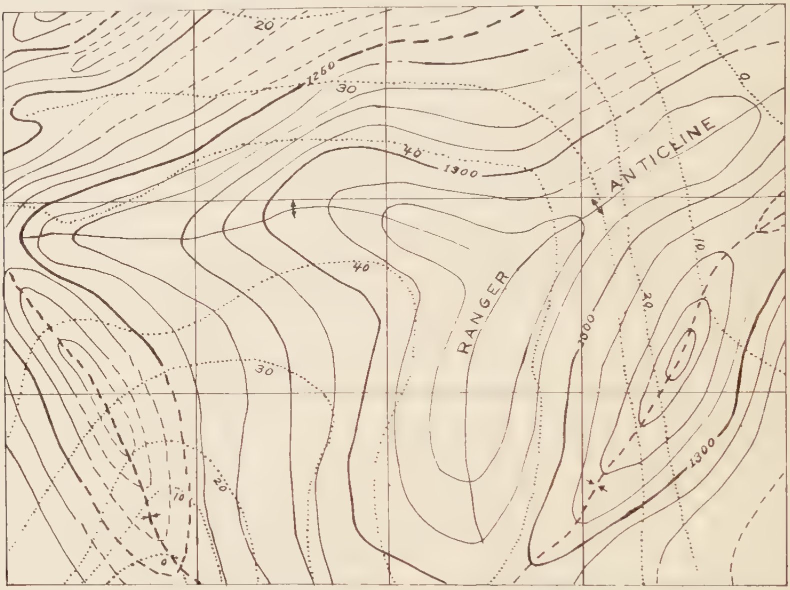


FIG. 129.—Map of a portion of the West Ranger area, Texas. Contours on the Upper surface of the Blank Lime. Dotted line shows thickness of sand. Adapted from Reeves, Frank: U. S. G. S. Bull. 736, Plate XIX, 1922.

The Ranger limestone of the Canyon formation, usually used in surface contouring, shows no break in the regional dip of 50 feet to the mile in a northwest direction. Slight bucklings accompanied by minor changes in the direction of the dip are the only evidence of folding. The axes in these minor wrinkles do conform rather closely to the direction and position of the larger folds in the Bend series. Some aid was given the prospector during the later stages of the development of the area when the meaning of these flexures had been determined by correlation of surface and subsurface maps. However, a greater element of structural uncertainty remained than in most of the world's producing areas.

The data available point to a period of folding beginning during the latter part of the deposition of the Marble Falls limestone. The interval between the McClesky sand and the top of the "Black lime" is between 170 and 185 feet in the southern part of the district and from 200 to 230 in the northern portion. The thickness of the strata in the synclinal areas is from 15 to 30 feet greater than in the anticlinal ones throughout the whole area. The occurrence of folding at this early time may have been responsible for the variations in the percentages of argillaceous and calcareous matter deposited in the different areas.

The major period of folding undoubtedly came at the close of the Bend time and was responsible for the development of the marked folds in the rocks of that series. The bottom of the Strawn rests unconformably upon the upper surface of the Bend series. It is probable that folding also occurred at the close of the Carboniferous. The absence of definite folds in the Upper Pennsylvanian indicates that this was of only slight importance. It is possible that many of the folds in this upper group of beds are due mainly to compacting.

La Salle Anticline, Illinois and Indiana.[1]—The first commercially successful well on the La Salle anticline was completed in 1904, near the town of Casey in eastern Illinois. The production came from a shallow sand. This encouraged rapid development, which resulted in extensions of the productive area northward and southward until it included pools extending for a length of 80 miles along the axis of the La Salle anticline. The greatest width of producing area was about 15 miles. The production rose to 33,000,000 barrels in 1910. Extensions have been made from time to time and new horizons opened by deeper drilling, which have tended to delay the natural decline so that the annual production is still about 7,000,000 barrels.

The La Salle anticline is a fold of the plunging anticlinal type; but because of its sharply defined form, it is considered as more closely related to the ordinary closed types. The axis of the fold may be definitely traced for nearly 200 miles. Its strike is slightly to the west of north. The productive part of the fold is its southern half. As in other folds of similar character, the axis contains domed and synclinal areas of varying size and importance. Two of the saddle-like depressions separate the producing area of Crawford County in Illinois from the producing areas of the Lawrence County pools to the south and from the pools to the north.

[1] Data mainly from:

Blatchley, R. S.: Illinois State Geological Survey Bull. 16, 1910; and Bull. 22, 1913.

Kay, F. H.: Geol. Soc. Amer. Bull., Vol. 28, pp. 655–666, 1917.

The lowest of the producing horizons, with the exception of the Trenton, which is of minor importance here, is the McClosky. It is an oölitic limestone of varying porosity and ranges from two to ten feet in thickness. The average thickness is close to the latter limit. Kay considers it to be a zone rather than a single continuous body. It is found in the St. Genevieve limestone of the Upper Mississippian.

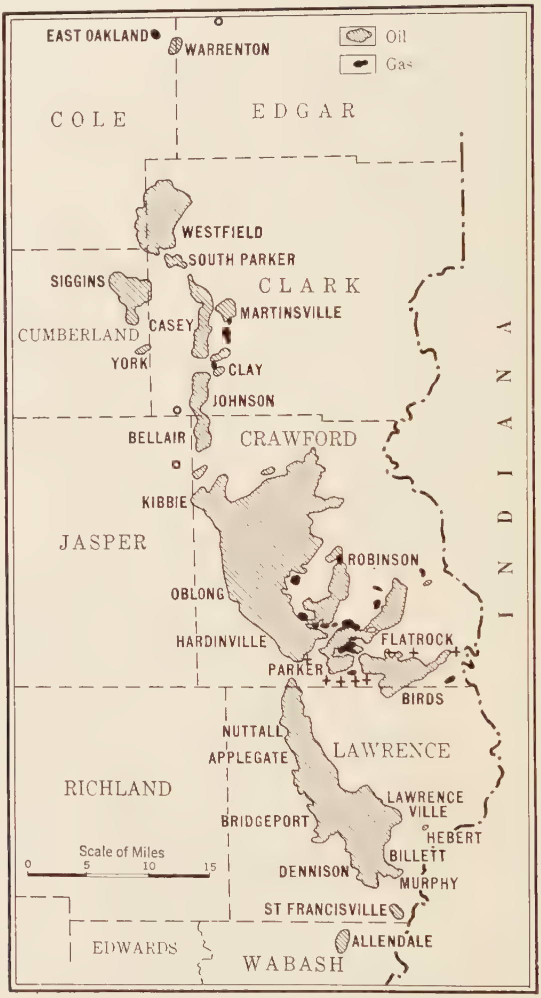


FIG. 130.—Map showing distribution of producing areas on the La Salle anticline in Illinois. Adapted from U. S. Geological Survey.

In some places as many as three closely related oil-bearing horizons have been reported. The maximum thickness of the zone is 80 feet.

The McClosky is the only one of the producing horizons that can be considered as continuous over the whole structure. In it accumu-

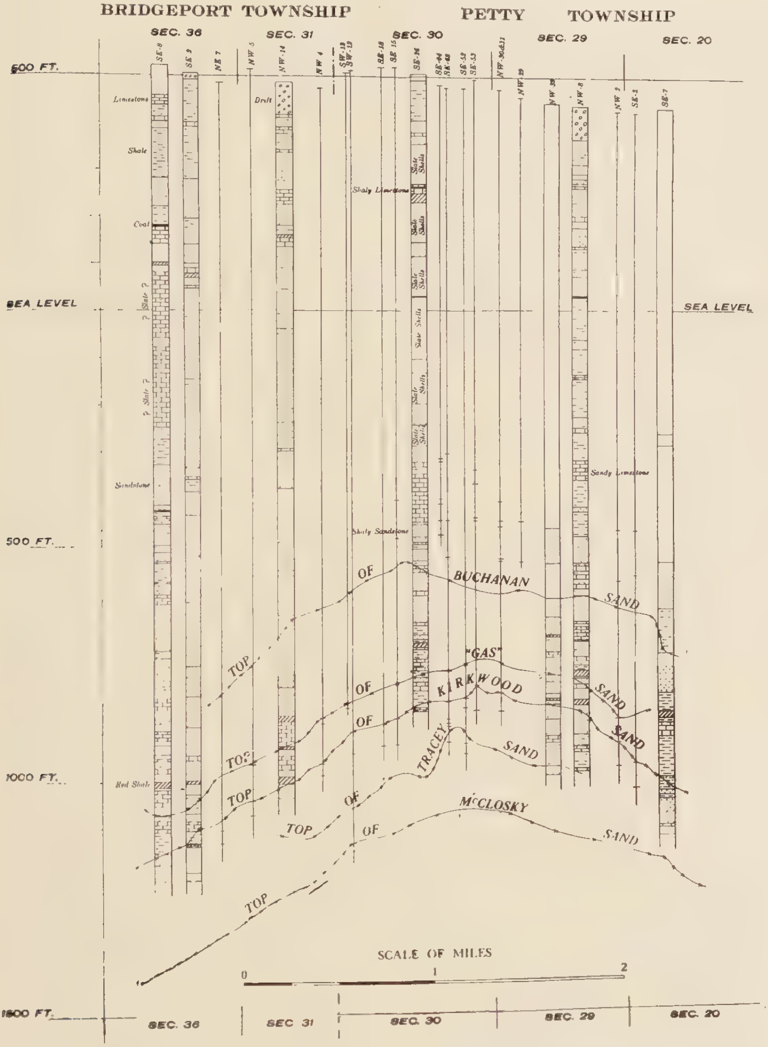


FIG. 131.—East-west cross-section of the La Salle Anticline through Bridgeport and Petty townships, Illinois. After Blatchley, R. S.: Ill. State Geol. Surv. Bull. 22, Plate XIV, 1913.

lation shows closer relationship to structure than it does in any of the others, but thinning and porosity variations are of major importance also. In the shallow northern pools, the McClosky lies within 350 feet of the surface. At the southern end of the field, it is between 1,750 and 2,000 feet deep. In the southern portion a number of shallower sands in the Pennsylvanian and Mississippian have been developed. Of these the best known are the Bridgeport, Buchanan, Kirkwood, and Tracey. All of them lense out to the north leaving the McClosky as the only producer of importance.

The accumulation of oil in these horizons follows structural lines in a general way wherever they are sufficiently continuous. However, salt water appears at various places higher structurally than nearby sections in which oil is obtained. This indicates considerable variation in porosity.

In the series of pools to the east of the main crest, such as New Hebron, Flat Rock, Parker, and Birds, the productive horizons are not visibly affected by folding. The oil-containing areas seem to correspond largely in areal extent with the thicker portions of lenticular sand bodies and to die out where the beds thin out. A delta origin has been ascribed to many of these irregular sand bodies.

The southeastern end of the fold is still a center of active prospecting, additional lenticular sands being discovered from time to time. The western edge is much steeper than the eastern. Along it the edge of the producing belt is clearly defined.

Kevin-Sunburst Area, Montana.[1]—The discovery well of this section was completed in 1922. In 1926 the daily average production was nearly 20,000 barrels. At the close of that year, 650 wells were producing. The productive area lies in Toole County in northern Montana. The character of the producing horizons is entirely different from that of any of the other major pools of the Rocky Mountain section. Its history has similarly been different from that of the others. The first well was located in Section 16, T. 35 N., R. 3 W. and was completed in March, 1922. It had produced from 500,000 to 1,000,000 cubic feet of gas from a sand near the base of the Colorado shale. It yielded a showing of oil at the base of the Kootenai formation and a few barrels of oil in the underlying Ellis. At the best the capacity was only five to ten barrels of oil a day. The second well was completed in June of the same year as a 200-barrel pumper. It was located in Section 34, T. 36 N., R. 2 W. Both wells were to the north of the center of the Sunburst dome, a major closure on the

---

[1] Data mainly from:

Hager, Dorsey: The Sunburst Oil and Gas Field, Montana, A. I. M. M. E. Trans., Vol. 69, pp. 1101–1120, 1923.

Anonymous: The Kevin-Sunburst Oil Field, Montana, U. S. G. S. Press Notices, September 7, 1922, and January 12, 1926.

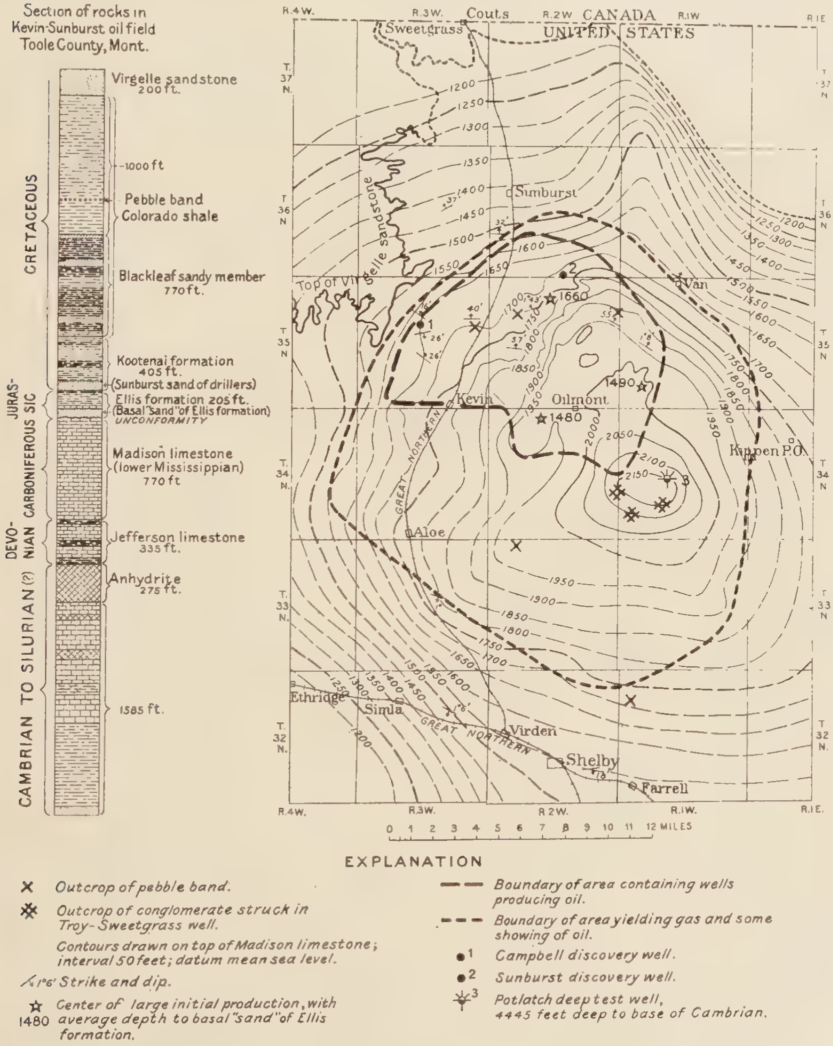

Section of rocks in Kevin-Sunburst oil field Toole County, Mont.
Virgelle sandstone 200 ft.
-1000 ft
Pebble band
Colorado shale
Blackleaf sandy member 770 ft.
CRETACEOUS
Kootenai formation 405 ft.
(Sunburst sand of drillers)
Ellis formation 205 ft.
(Basal "Sand" of Ellis formation)
UNCONFORMITY
JURASSIC
Madison limestone (lower Mississippian) 770 ft
CARBONIFEROUS
Jefferson limestone 335 ft.
DEVONIAN
Anhydrite 275 ft.
1585 ft.
CAMBRIAN TO SILURIAN(?)
R.4W.
R.3W.
R.2W.
R.1W.
R.1E.
T. 37 N.
T. 36 N.
T. 35 N.
T. 34 N.
T. 33 N.
T. 32 N.
CANADA
UNITED STATES
Coutts
Sweetgrass
Sunburst
Top of Virgelle sandstone
Van
Kevin
Oilmont
Kippen P.O.
Aloe
Ethridge
Simla
Virden
Shelby
Farrell
GREAT NORTHERN
1480
1490
1660
0 1 2 3 4 5 6 7 8 9 10 11 12 MILES
EXPLANATION
Outcrop of pebble band.
Outcrop of conglomerate struck in Troy-Sweetgrass well.
Contours drawn on top of Madison limestone; interval 50 feet; datum mean sea level.
Strike and dip.
Center of large initial production, with 1480 average depth to basal "sand" of Ellis formation.
Boundary of area containing wells producing oil.
Boundary of area yielding gas and some showing of oil.
1 Campbell discovery well.
2 Sunburst discovery well.
3 Potlatch deep test well, 4445 feet deep to base of Cambrian.

FIG. 132.—Map of the Kevin-Sunburst Area, Montana. After U. S. Geol. Survey, Press Notice, Jan. 12, 1926.

still larger Sweetgrass uplift. They were followed by rapid drilling of other wells. None of these were very large producers and development work was hindered considerably by the spottiness of the productive areas.

The oil is obtained mainly from the base of the Ellis formation, but the Sunburst sand of the Kootenai is also important. It is especially prominent as a producer of gas. The Kootenai formation is of Lower Cretaceous age and about 400 feet thick. It is composed of sandstones and varicolored shales. The Sunburst sand is the lowest member of the formation. It varies from five to 50 feet in thickness. The extreme lenticularity of the horizon greatly limits its value. The Ellis formation lies below it. This is 200 to 250 feet thick and consists mainly of shaly sandstones and limestones. At its base lies the productive portion, a sandy limestone between five and ten feet thick. Several stray sands have been found in the Ellis also.

The Ellis formation is considered to be of Jurassic age. It rests unconformably upon the Madison limestone of the Lower Mississippian. The lower productive sand is more continuous than the Sunburst but is like it in being of highly variable character. In some places it is a typical conglomerate, made up of more or less rounded pebbles of fossiliferous Madison limestone and quartzite with angular fragments of secondary silica and pyrite. In others the horizon is a slightly cavernous limestone in the top of the Madison.

The Sunburst pool as outlined to the close of 1926 included all of T. 35 N., R. 2 W. and substantial areas in adjacent townships. The gas area to the south of the oil pool and the areas in which wells have shown small amounts of oil would include a much larger section. Up to the present the oil has been limited, as far as commercial production is concerned at least, to the northwest side of the broad Sunburst dome. Tests in other areas, while indicating the presence of oil, have not found sufficient thicknesses of sand to make commercial wells.

The dip throughout the area north of the crest averages only 50 feet to the mile. The contours of the major dome are probably complicated by a number of minor folds, which are of some importance in determining areas of maximum production. They do not show up clearly upon 50-foot contour maps and are believed to play a minor part in accumulation. The wide variations in productivity between wells short distances apart are generally attributed to the irregular character of the erosion surface horizons in which the accumulation has occurred.

Binagadi, Russia.[1]—Normally a fault is expected to yield oil from one side only. It is possible that where the fault is combined with folding for both sides to serve as accumulation and retention areas. Binagadi pool, one of the most important of the structures in the Apsheron peninsula, or Baku district of Russia, is of this type. Prior to faulting the area was apparently arched up in the form of a definite anticline. It is possible that the faulting did not occur until after the accumulation of the oil had been partly accomplished. In that case the importance of the fault lies mainly in its division of the producing tract into two isolated areas. In these, edge-water encroachment and other production problems will be entirely distinct.

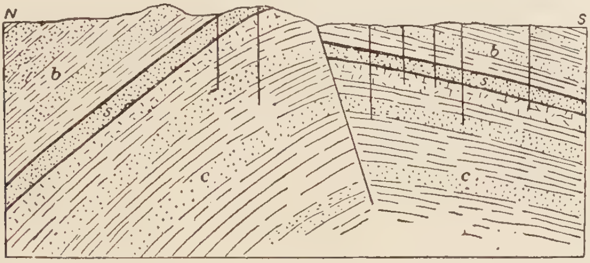


FIG. 133.—Section through the Binagadi oil pool, Russia. *b*, Freshwater beds, Miocene; *c*, Lower Miocene; *s*, Spiralis beds. After Thompson, A. B.: Inst. Min. & Met. Trans., Vol. 20, p. 229, 1910–11.

Where the faulting took place after the accumulation within the fold and the two sides were subject to the same geologic forces, the conditions within the horizons should be much the same on both sides. This, however, is not true in Binagadi, where the wells on one side are of larger average size than those on the other. As the productive horizons are the highly unconsolidated sedimentary sands of the Tertiary, the differences cannot be considered as due to variations within the sand bodies. It seems more logical to conclude that the faulting occurred prior to the bulk of the accumulation and that drainage from one side was greater than that from the other. It appears to have resulted in accumulation of unequal amounts and the development of unequal pressures.

Inglewood, California.[2]—A somewhat similar condition is found

[1] Thompson, A. Beeby: Inst. Min. & Met. Trans., Vol. 20, p. 229, 1910–11.

[2] Data mainly from:

Huguenin, E.: Inglewood Oil Field, California Oil Fields, Vol. 11, No. 12, 1926.

in the Inglewood pool in the Los Angeles Basin of California. In this pool, however, the fault is off to the side of the main structure rather than crossing its center. There is reason for the assumption that the faulting and the part of the folding which accompanied it came after the accumulation had begun. The more productive area is that which lies on the downfaulted western portion, the section embraced by the major portion of the fold.

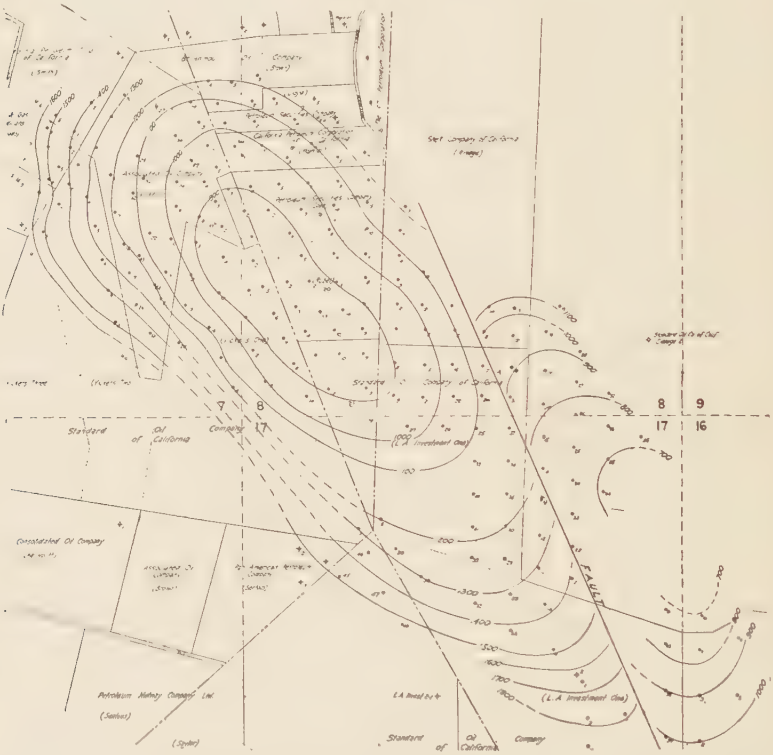


FIG. 134.—Structure map of the Inglewood oil pool, California. Contours on top of oil sand. Datum sea level. After Huguenin, E.: California Oil Fields, Vol. 11, No. 12, Plate 2, 1926.

The Inglewood structure is one of the series lying along the Inglewood fault or uplift zone. Because of the prominence of the Baldwin Hills, the most striking topographic feature of the vicinity, it had been a center of interest for some time. It was not until 1924, however, that the first commercial well was completed. By the close of 1926, the cumulative production had reached the total of 43,000,000 barrels. The oil was taken from an area of about 1,200 acres and wells found the productive horizons between 1,200 and 3,150 feet below the surface.

Operating conditions are much the same as in other pools of the Los Angeles Basin, the oil being contained in zones of interbedded sands and clays of great thickness. The first and smaller zone was reached at a depth of about 1,200 feet. It produced through a depth of 600 feet when first opened up, but edge water rapidly reduced its value. The oil was of 13 to 18° Baume gravity. Below this edge water, the main producing horizon was found. This yielded wells of 1,000 to 4,000 barrels capacity and produced oil of 18 to 29° gravity. In a general way conditions on both sides of the fault have been found to be much the same. Edge water has been encountered in positions down the dip on the east side similar to those on the west side. The lower producing horizon is considerably smaller in vertical extent on the east side than on the west. Thus while wells on the crest east of the fault have about 1,000 feet of productive formations, those on the west crest have been developed through a thickness of 1,300 feet. In one case a thickness of 1,700 feet was reported.

In productive zones of such great thickness, the ability of a fault, even as large as the one present, to isolate the two areas is open to question. Its throw of 350 to 400 feet does not separate the producing zones completely. However, the large amount of clay and other impervious matter present in the zones has undoubtedly tended to restrict the movement from one side to the other. That it has been effective may be inferred from the somewhat higher Baume gravity of the oil on the east side of the fault.

Hubbard Pool, Oklahoma.[1]—In the examples just discussed, the planes of the faulting have been nearly vertical. The conditions in the different horizons were much the same. In the Hubbard pool in western Kay County, Oklahoma, a fault having an angle of 45 degrees makes the conditions at various depths materially different. The pool is closely related to a number of others in which production has been obtained from eroded surfaces of Ordovician limestones. The first well completed obtained production in a deep horizon found between 3,754 and 3,761 feet. This was considered as being the Wilcox sand. The production was large but fell off rapidly. Shortly after this a well half a mile north of the discovery test obtained production from a sand found at 2,600 feet. The wells in this horizon appeared to be considerably more desirable from the commercial standpoint than those found in the first discovery. Because of this the latter half of 1924 and all of 1925 were devoted to drilling to the shallower depth. Other sands were found to be productive, but their value was not as great as that of the 2,600-foot horizon. This was largely responsible for the total of more than half a million barrels produced in 1925. Later, wells were deepened to the Wilcox in the central portion of the pool and additional oil was obtained.

---

[1] Data mainly from an anonymous article containing maps by A. F. Truex: Hubbard pool has geologists guessing, Oil and Gas Journal, Vol. 24, pp. 81–82, Oct. 15, 1925.

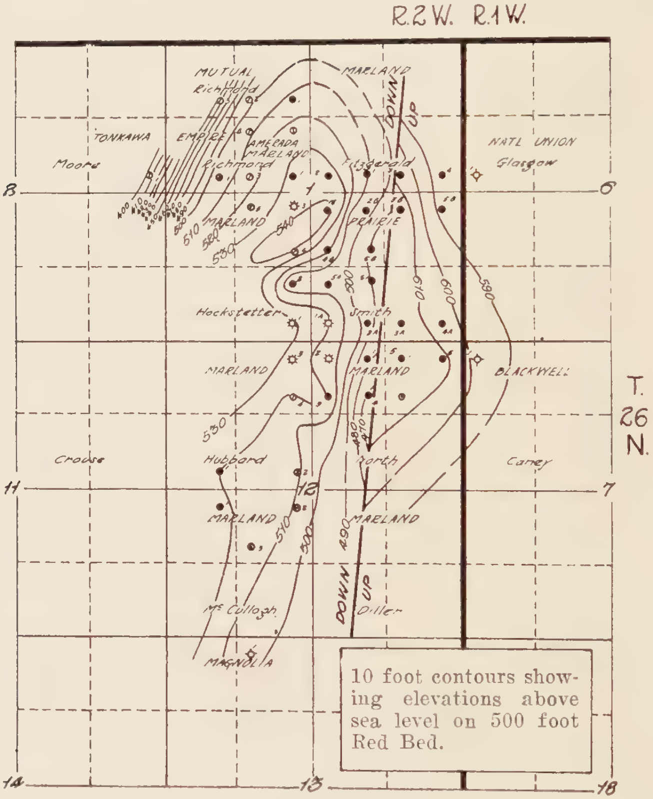


FIG. 135.—Hubbard pool, Oklahoma. After Truex, A. F.: Oil and Gas Journal, October 15, 1925, p. 81.

The development of the 2,600-foot horizon demonstrated the downward continuation of a fault which had been noted in the upper red-beds. The contours drawn upon a prominent red-bed found at a depth of about 500 feet show a fault crossing a folded area and having a maximum throw of 140 feet, with the downthrow to the west. The contours drawn upon a 2,000-foot sand horizon and upon the 2,600-foot bed show the throw to be about the same in amount but indicate considerable change in the position of the fault and in the nature of the folds adjacent to it. In these the fault is indicated as dipping to the west at an angle of about 45 degrees. Its trace for the deeper beds is thus considerably west of its trace in the upper ones. Thus wells that appeared to be located on the west side of the fault were actually obtaining their production from the east side. The production of wells actually west of the fault has been relatively small and the limited area largely defined by dry holes.

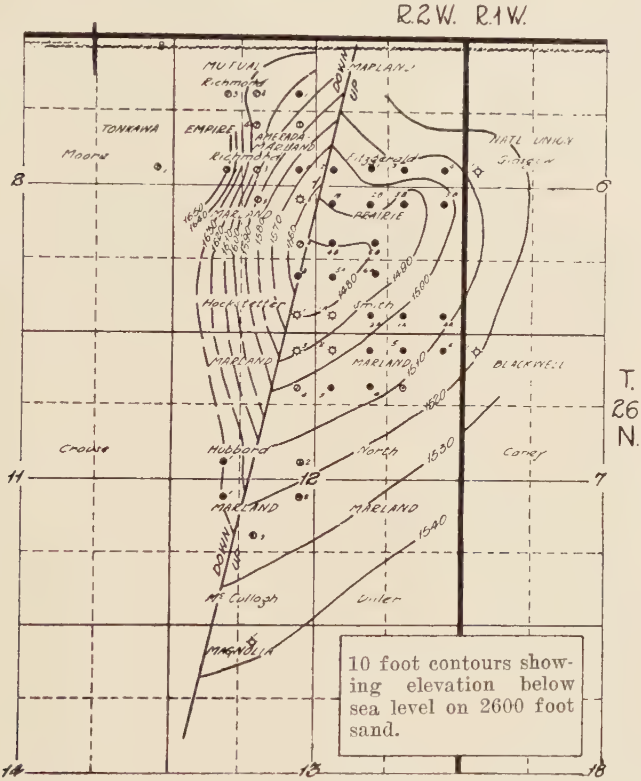


FIG. 136.—Hubbard pool, Oklahoma. After Truex, A. F.: Oil and Gas Journal, October 15, 1925, p. 81.

Sufficient testing has been done to indicate that the Wilcox horizon is of greater extent than the upper production, but the close control held by a few corporations has tended to retard the development of that horizon. When fully developed, its producing areas will probably be found to be limited by the same factors that are present in Tonkawa, which is described on page 465.

Salt Creek, Wyoming.[1]—The faulted and folded pools cited in this chapter have been of comparatively small size. In the Salt Creek structure, we have one of the largest of the anticlinal folds that are productive of oil. The productive area differs from that in other structures in the Rocky Mountains in being of extent comparable with the closure of the fold rather than being limited to a small section of the very highest portion. Up to the present the bulk of the production has come from two sands: the First Wall Creek and the Second Wall Creek. Below these others have been tested and have yielded some oil. The structure while distinctly an anticlinal fold is not entirely regular in outline. Its southern portion, called the Teapot Dome, is separated from the main area by a saddle and several faults. In addition, while the two main horizons are productive over a considerable area, there are several lensing horizons, and some production has been obtained from wells encountering fissures in shales.

The structure was known in a general way as early as 1880 because of the size of the uplift and the presence of several active seepages. The Shannon pool, a small shallow productive area north of the main development, was discovered in 1889. While some oil was shipped from this, the main development did not begin until 1908 when the First Wall Creek sand was discovered. Title difficulties

---

[1] Data on Salt Creek mainly from:

Armstrong, R. O., and Rader, C. M.: Water Shut-off Methods in the Salt Creek Field, Petroleum Development and Technology in 1925, pp. 265–277.

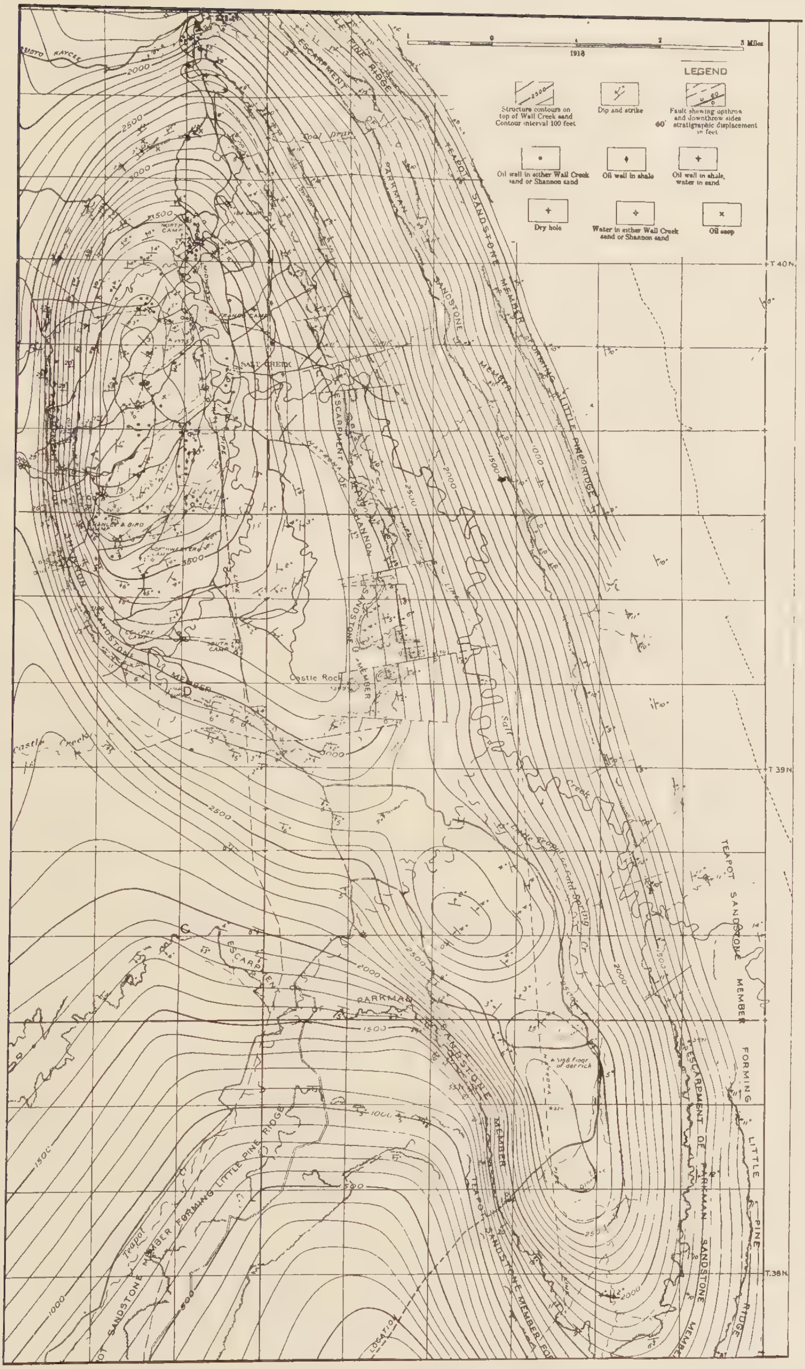
Clapp, F. G.: Report on Teapot Dome Naval Reserve No. 3, Wyoming, before U. S. Senate Committee on Public Lands and Surveys, Oct. 22, 1923.

Lewis, J. O.: Report of the geological conditions of Teapot Dome (Naval Reserve No. 3, Wyoming), before U. S. Senate Committee on Public Lands and Surveys, Oct. 22, 1923.

Estabrook, E. L., and Rader, C. M.: History of Production of Salt Creek Field, Pet. Dev. and Tech. in 1925, pp. 199–254.

Wegemann, C. H.: The Salt Creek Oil Field, Wyoming, U. S. G. S. Bulletins, No. 452, 1911, and No. 670, 1918.

Young, H. W., and Estabrook, E. L.: Waters of the Salt Creek Field, Wyo., Pet. Dev. and Tech. in 1925, pp. 255–277.



1
0
1
2
3 Miles
1918
LEGEND
Structure contours on top of Wall Creek sand Contour interval 100 feet
Dip and strike
Fault showing upthrow and downthrow sides
60' stratigraphic displacement in feet
Oil well in either Wall Creek sand or Shannon sand
Oil well in shale
Oil well in shale, water in sand
Dry hole
Water in either Wall Creek sand or Shannon sand
Oil seep
T 40 N.
T 39 N.
T.38 N.
2000
2500
3000
3500
1500
1000
500
LITTLE PINE RIDGE
ESCARPMENT OF PARKMAN
TEAPOT SANDSTONE MEMBER FORMING LITTLE PINE RIDGE
Coal Draw
NORTH CAMP
SALT CREEK
ESCARPMENT OF SHANNON SANDSTONE MEMBER
SHANNON SANDSTONE MEMBER
HANLEY & BIRD
NORTHWESTERN
ECLIPSE CAMP
SOUTH CAMP
Castle Rock
Castle Creek
Salt Creek
D
C
ESCARPMENT
PARKMAN SANDSTONE MEMBER
TEAPOT SANDSTONE MEMBER FORMING LITTLE PINE RIDGE
TEAPOT SANDSTONE MEMBER
ESCARPMENT OF PARKMAN SANDSTONE MEMBER
Teapot
LOCATION

FIG. 137.—Map of the Salt Creek anticline. After Wegemann, C. H.: U. S. G. S. Bull. 670, Plate I, 1918.

restricted development somewhat, but the area soon became the most important source of oil in the Rocky Mountains.

In 1917 the Second Wall Creek was proved productive. In 1921 the Lakota sand was penetrated and proved to be oil-bearing. Up until the close of 1924 very little oil had been taken from below the Second Wall Creek. The production of the different zones up to that time was approximately 138,000,000 barrels. Of this, the Second Wall Creek had contributed 106,500,000, and the First Wall Creek and shale fissures 29,500,000 and 2,200,000 respectively. In the years of 1925 and 1926 a substantial production was obtained from the Lakota and other horizons below the Second Wall Creek. The total production during these two years was 39,000,000 barrels. In addition about 5,000,000 barrels have been taken from the naval reserve land on Teapot Dome since 1922.

As originally mapped by Wegemann, the structure was divided into a major northern dome and a small terrace-like extension to the south. In this extension, two subordinate domes were mapped. The crest of the major or Salt Creek portion was considered to coincide with the 3,900-foot contour of the First Wall Creek sand. The crest of the northernmost of the two minor domes was placed between 2,900 and 3,000 feet above sea level. The elevation of the saddle between it and the major dome was considered to be between 2,700 and 2,800. The crest of the southernmost dome was placed between 2,700 and 2,800 and the saddle north of it, at 2,500 to 2,600. The lowest structural line completely circling the whole area was the 2,700-foot one, as the dip to the west of the main structure, while steeper than in any of the other parts, was reversed within a short distance to the west of the crest.

The axial plane of the fold dips somewhat to the east so that the axis in the lower formations are somewhat to the east of those in the shallower beds. The shift is not of major importance.

In mapping the area Wegemann showed a number of faults at right angles to the axis of the fold. These he found to be most prominent along the southeastern edge of the Salt Creek dome proper. They varied in vertical intensity from a few feet to 130 feet. The faulting was accompanied by horizontal movement, this being placed in one case at 2,670 feet. The faults noted were all of approximately the same strike, north 80 degrees east. Being at right angles to the strike of the beds containing the oil, they had little effect upon its accumulation and production except in the southern portion. At the time of making his report, Wegemann pointed out the fact that the anticlinal axis is bent sharply between the Salt Creek dome and the two domes of the Teapot area and suggested the possibility of faulting in that area.

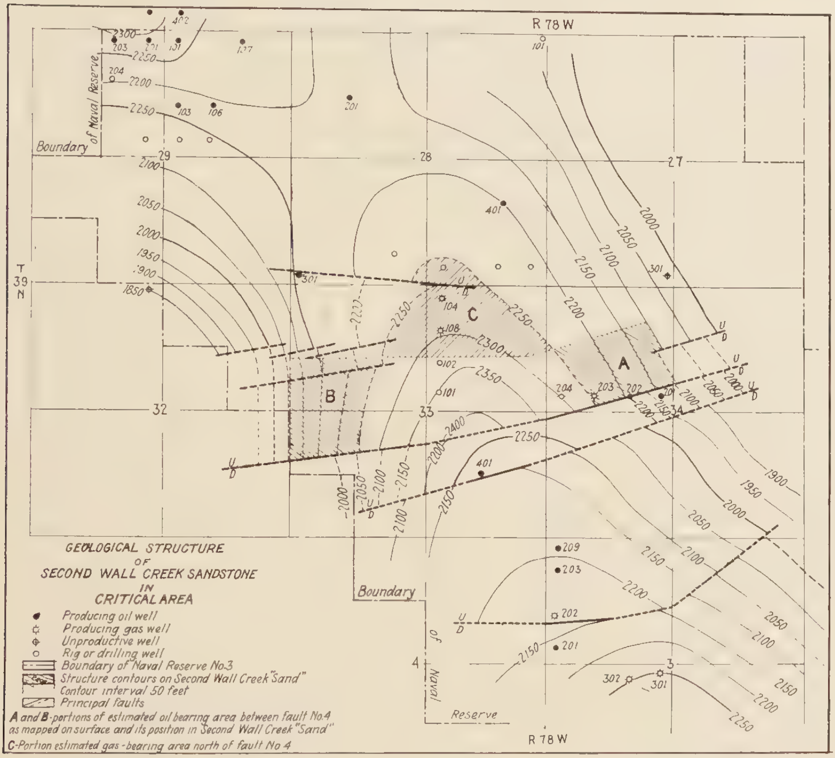

R 78 W
T 39 N
Boundary of Naval Reserve
29
28
27
32
33
34
4
3
A
B
C
U
D
Boundary of Naval Reserve
R 78 W
GEOLOGICAL STRUCTURE OF SECOND WALL CREEK SANDSTONE IN CRITICAL AREA
● Producing oil well
☼ Producing gas well
⊕ Unproductive well
○ Rig or drilling well
Boundary of Naval Reserve No.3
Structure contours on Second Wall Creek "Sand"
Contour interval 50 feet
Principal faults
A and B-portions of estimated oil bearing area between fault No.4 as mapped on surface and its position in Second Wall Creek "Sand"
C-Portion estimated gas-bearing area north of fault No 4

FIG. 138.—Structure map of the Second Wall Creek Sand in area between Salt Creek and Teapot Dome. After Clapp, F. G.: Report on Teapot Dome Naval Reserve No. 3, Wyoming, before U. S. Senate Committee on Public Lands and Surveys, Oct. 23, 1923.

At the time the field examination was made, the First Wall Creek sand was the source of practically all of the oil. The water level in this sand was at that time between 400 and 500 feet below the crest of the dome and gave definite evidence that the producing area did not extend into the saddle. The Teapot Dome naval reserve was established on that basis and made to include all of the area of the two southern domes and half of the saddle to the north of them.

More detailed work subsequent to the establishment of the reserve tended to indicate the probability of the modification of the form of the saddle and of the northern of the two small domes by faulting. The productive area in the Second Wall Creek was found to be far greater than that of the First Wall Creek. Development southward from the center of the producing area continued until wells were producing from the northern part of the saddle area. The naval reserve was then leased to the Mammoth Oil Company. Drilling was started along the northern edge of the naval reserve in 1922 and a series of test wells put down at various points to the south. The development of the area was terminated by a suit on the part of the United States Government to recover the leased lands. Prior to this a number of wells had been drilled. They demonstrated the nonexistence of oil in the First Wall Creek sand and the presence of an unexpectedly large amount of gas in the Second Wall Creek. The distribution of the gas and the oil was very irregular and indicated definitely the presence of important faults. These were studied by F. G. Clapp and J. O. Lewis, who had been commissioned by Congress to report on the technical phases of the leasing.

In all 33 faults were found by them in the Teapot Dome section. Only a few of these were of major importance, that is, of sufficient throw to sever the thick Second Wall Creek sand. Three, known as faults number 4, 6 and 25, were of greater importance than any of the others. Number 4 had a south dip of 50 degrees and a displacement of 270 feet. Its strike was nearly east-west. It was located in Section 33. Just south of this fault lies number 6. Its strike is north 70 degrees east and indicates the possibility of it merging with number 4. The downthrow was again to the south and appeared to be more than 70 feet. Fault number 25 was located in Section 3. The strike on this fault shifts from east-west to north 50 east. The throw was to the south and was considered to be at least 40 feet.

Fault number 4 completely crosses the structure. North of it the arching of the beds produced a closed trap in which gas was found close to the fault. Oil was found in the area between it and number 6; but close to the north side of number 25, free gas was obtained. This section was also domed in character. Immediately south of number 25 oil was obtained, but in the southern dome gas appears to occupy most of the closure.

The large quantity of free gas in the Teapot Dome is in direct contrast to the conditions in the Second Wall Creek sand throughout the major closure. There the gas was practically all dissolved in the oil.

The differences between conditions south of the saddle and faults and those on the main structure can only be explained by the existence of these limiting structural features and the poorer quality of the small domed areas as areas of accumulation. It cannot be explained by variations in the porosity of the horizon. While the Second Wall Creek contains shale partings and varies from 20 to 100 feet in thickness, it is continuous over the whole structure. The same is true of the First Wall Creek sand.

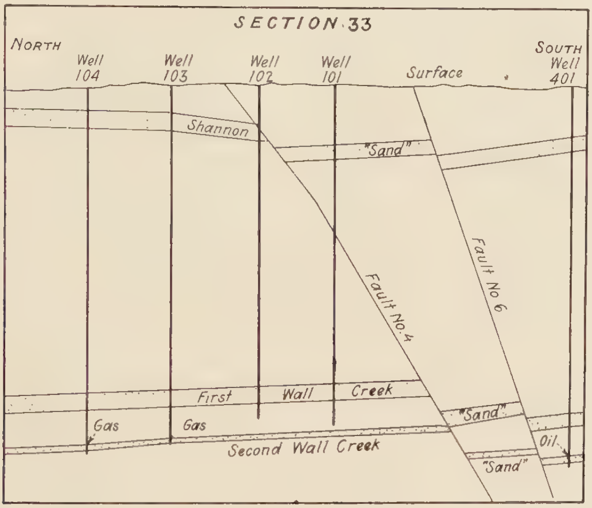


FIG. 139.—North-south section through section 33 between Salt Creek and Teapot Dome showing effects of faulting. After Clapp, F. G.: Report on Teapot Dome Naval Reserve No. 3, Wyoming, before U. S. Senate Committee on Public Lands and Surveys, Oct. 23, 1923.

The Shannon has only been found to contain oil in a small area in the northern part of the main fold. This formation has been removed from a considerable area, and the oil that it may have contained originally has been allowed to escape. In parts of the structure production has been obtained from what is known as the Third Wall Creek sand. This lies about 625 to 675 feet below the top of the First Wall Creek. It is extremely lenticular in character and therefore of uncertain value. The same may be said of sands in the Dakota.

The Lakota, which lies below the Dakota, is a sand of about 70 feet thickness. Like the two important Wall Creek horizons, it appears to be continuous and its production to conform to structural conditions. Recent deep testing has shown the existence of oil in the sands of the Sundance and Morrison formations. Sufficient work has not yet been done to determine the importance of these, but the Lakota is now a substantial producer.

In addition to the production from the regular horizons, a considerable amount of oil has come from crevices, or shale fissures. These were most prominent in the shale above the First Wall Creek but are now yielding considerable oil from points between the lower Frontier and the Lakota sands also.

Cat Creek, Montana.[1]—While the productive area is considerably smaller, somewhat similar conditions to those of the southern part of the Salt Creek-Teapot Dome anticline are found in the Cat Creek pool in central Montana. This area was the first to be developed in the state of Montana, the discovery well being completed in 1920. The peak production came in the summer of 1922 when 8,500 barrels were obtained daily. The cumulative production to the close of 1926 was about 9,000,000 barrels. The oil has a gravity of 47 to 50° degrees Baume, making it one of the most valuable oils produced in the world.

The oil has been taken mainly from two domes upon the major anticlinal fold known as the Cat Creek anticline. This comparatively narrow fold extends eastward from the vicinity of the Judith Mountains for a distance of 70 miles. Eight distinct domes separated by saddles have been located along its crest and given names. The structure of each of them is complicated by a series of faults. Only two of them, the West dome and the Mosby dome, both in the eastern half of the major fold, have been found to contain commercial quantities of oil.

Petroleum was first found in the Mosby dome. The discovery well was small and wells drilled near it proved unpromising. Up to July, 1926, only 22 commercially productive wells had been completed on this dome. Development of the West dome followed shortly after that on the east and demonstrated the presence of a considerably greater, although badly broken up, oil-containing area. Here 190 producing wells were completed.

The productive horizons are the First and Second Cat Creek sands.

---

[1] Data mainly from:

Lupton, C. T., and Lee, Wallace: Geology of the Cat Creek oil field, Fergus and Garfield Counties, Mont., A. A. P. G. Bull., Vol. 5, pp. 252–275, 1921.

Reeves, Frank: Geology of the Cat Creek and Devils Basin Oil Fields, and Adjacent Areas in Montana, U. S. G. S. Bull. 786-B, pp. 39–95, 1927.

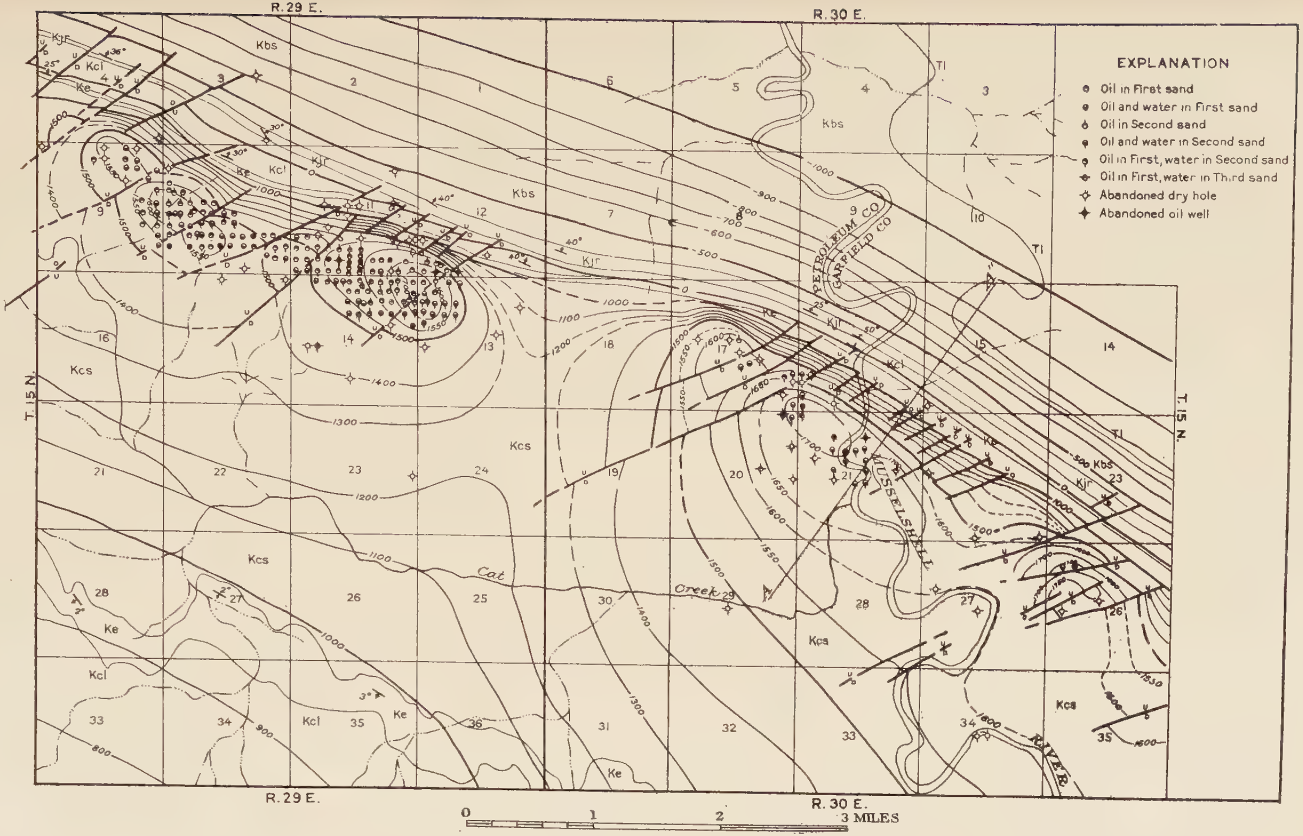


FIG. 140.—Producing areas of the Cat Creek anticline. Contours on the top of the First Cat Creek sand. After Reeves, Frank: U. S. G. S. Bull. 786, Plate 3, 1927.

A Third Cat Creek sand has been found in some wells but has not proved to be commercially valuable. The first sand was reached on the crest of the West dome at a depth of 1,100 to 1,400 feet. It occurs at the base of the Colorado shale. The second sand lies 160 to 235 feet below the top of the first. It is placed in the Kootenai formation. Both horizons are water-bearing, the edges of the producing areas being marked by flowing artesian water wells. The First Cat Creek sand is the more important producer on the West dome, but the Second Cat Creek is the source of the bulk of the oil on the Mosby dome.

There is no reason to consider that the doming was not the main cause in the accumulation of the oil. Yet the distribution of the oil-producing areas indicates that faults have played an important part also. The source of the oil is considered to have been the Colorado shales. From these the oil probably migrated into the First Cat Creek immediately below. The vertical movement in most of the faults appear to have been considerably less than the horizontal. In some cases, however, the vertical component has been as much as 150 feet and even more. This would bring the Second Cat Creek in contact with the First Cat Creek and permit the oil to move from the latter to the first.

The faults are also considered to have directed the movement of ground water, and to have served to prevent the development of the full flushing action of those waters. Thus the arched areas adjacent to the faults crossing the major domes have proved to be the most highly productive sections. Even in areas away from the main domes, some oil has been found trapped in the arches adjacent to faults.

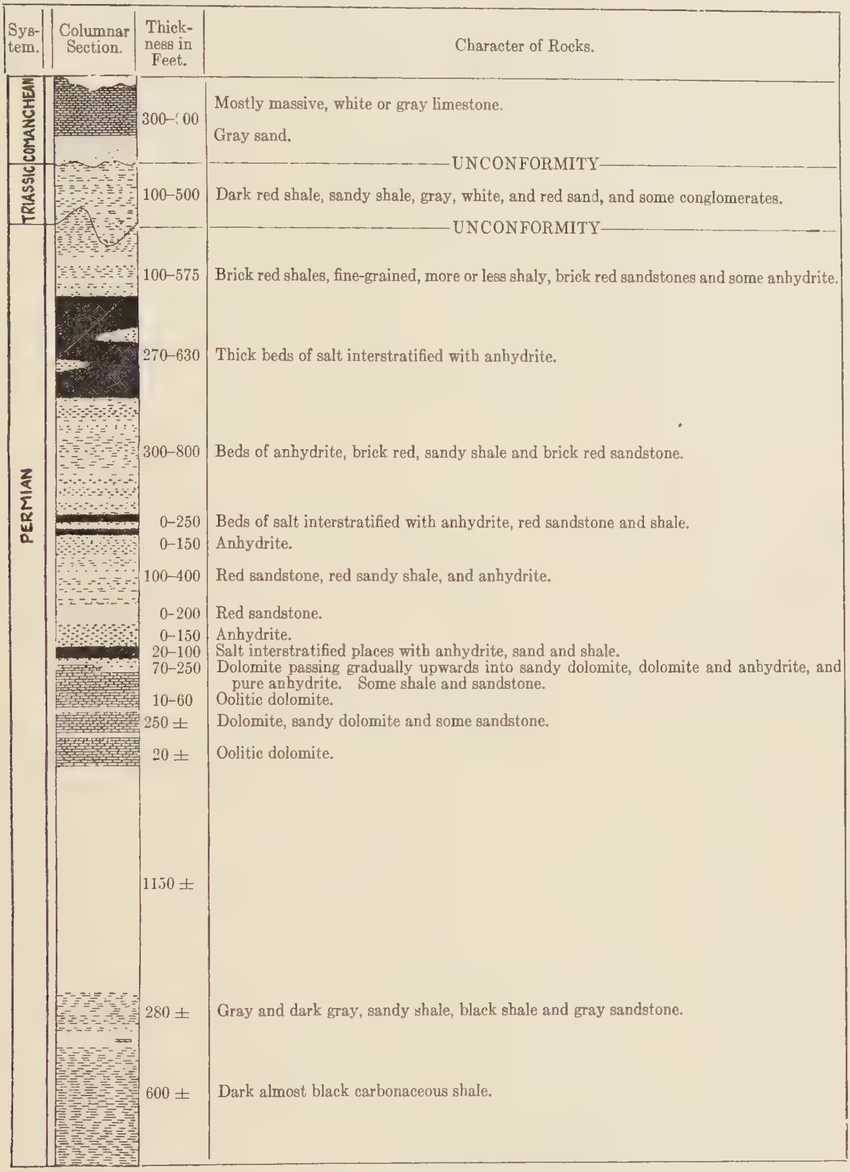
Such minor areas have been of little importance, except from the scientific standpoint, as their production has been obtained from only two or three wells. However, the accumulation of any oil is in direct contrast to its utter absence in some of the large less faulted domes on the Cat Creek anticline. In these the flushing action of the moving artesian waters has apparently removed all of the oil.

Big Lake Pool, Texas.[1]—The simplicity of the structure of the producing horizon of the Big Lake pool of Reagan County in western Texas makes a discussion of it in this chapter a little out of place. It

---

[1] Data mainly from:

Sellards, E. H., and Patton, L. T.: The Subsurface Geology of the Big Lake Oil Field, A. A. P. G. Bull., Vol. 10, pp. 365–381, 1926.



System.	Columnar Section.	Thickness in Feet.	Character of Rocks.
COMANCHEAN		300–[illegible]00	Mostly massive, white or gray limestone. Gray sand.
			UNCONFORMITY
TRIASSIC		100–500	Dark red shale, sandy shale, gray, white, and red sand, and some conglomerates.
			UNCONFORMITY
PERMIAN		100–575	Brick red shales, fine-grained, more or less shaly, brick red sandstones and some anhydrite.
		270–630	Thick beds of salt interstratified with anhydrite.
		300–800	Beds of anhydrite, brick red, sandy shale and brick red sandstone.
		0–250	Beds of salt interstratified with anhydrite, red sandstone and shale.
		0–150	Anhydrite.
		100–400	Red sandstone, red sandy shale, and anhydrite.
		0–200	Red sandstone.
		0–150	Anhydrite.
		20–100	Salt interstratified places with anhydrite, sand and shale.
		70–250	Dolomite passing gradually upwards into sandy dolomite, dolomite and anhydrite, and pure anhydrite. Some shale and sandstone.
		10–60	Oolitic dolomite.
		250 ±	Dolomite, sandy dolomite and some sandstone.
		20 ±	Oolitic dolomite.
		1150 ±	
		280 ±	Gray and dark gray, sandy shale, black shale and gray sandstone.
		600 ±	Dark almost black carbonaceous shale.

FIG. 141.—Generalized section in the Big Lake oil pool. After Sellards, E. H., and Patton, L. T.: A. A. P. G. Bull., Vol. 10, p. 369, 1926.

is one of the finest examples of completely buried structure that we have and as such is closely related to the complex structures of the covered and revived types which will be discussed after it.

The pool was opened up in 1923. At the time it was entirely isolated from any other producing areas. The development was slow at first, but later with the drilling of a number of large wells the pool became one of the more prominent areas of the state. Production to the end of 1926 amounted to more than 20,000,000 barrels. The single productive horizon was found at about 3,000 feet and yielded an oil of 39° Baume.

To the geologist the Big Lake structure is of interest primarily because of the perfection of the dome outlined by the drill and the entire absence of indications of that structure in the surface formations. The surface beds are of Comanchean age and the producing horizon lies in the Permian. This is an oölitic dolomite varying in thickness from 10 to 60 feet and averaging about 20 feet. The oölites are numerous. They vary in size from 0.2 mm. to 5 mm. in

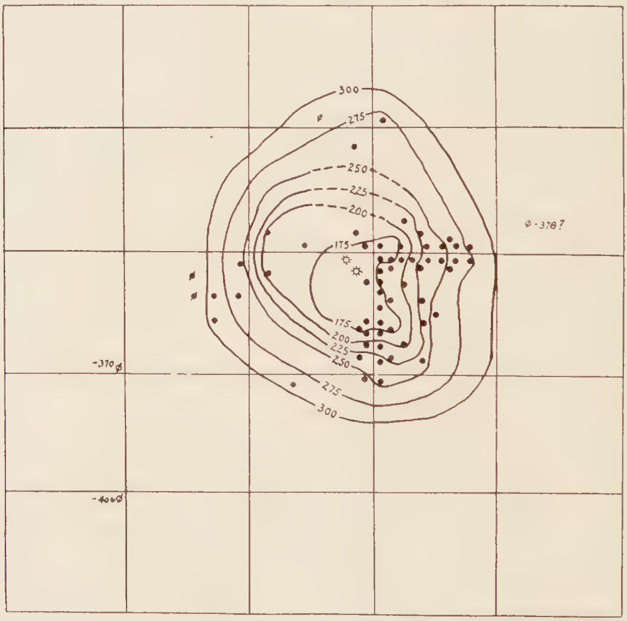


Fig. 142.—Structure map of the Big Lake oil pool. Contours on the oölitic zone of the producing horizon. After Sellards, E. H., and Patton, L. T.: A. A. P. G. Bull., Vol. 10, p. 378, 1926.

diameter and generally show a central body or nucleus of a sand grain. Except for this nucleus the horizon is made up of relatively pure dolomitic or, in parts, calcitic limestone.

The productive area has been found to coincide with a definite closure on the contour map of the oölitic dolomite. The dome of the producing horizon was found at a subsea level of 160 feet, and production extended down the sides to about 350 feet below sea level. The closure on the oölitic horizon was found to be reflected in the overlying salt, gypsum, and red-beds of the later Permian. A definite unconformity separates the Permian and the Triassic. The latter varies in thickness from 100 to 500 feet, variations depending largely upon the position of the upper surface of the Permian. Another but less marked unconformity separates the Triassic from the Comanchean. The thickness of the latter averages 500 feet.

The only possible reflection of the buried structure in the Comanchean is that the dip on a water sand near the base of beds of that age shows a slight terrace. To the west of the center of the Permian structure, the dip appears to be above the normal, while to the east it is slightly below the normal.

Healdton, Oklahoma.[1]—The Healdton pool in Carter County, Oklahoma, was probably the first pool in which the importance of the irregular surface of underlying hills which had been covered by later sedimentation was recognized. The pool was the largest of a group of closely related structures lying south of the Wichita and Arbuckle Mountains and north of the Red River. The discovery

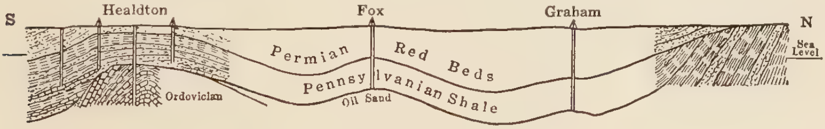


FIG. 143.—Generalized cross-section of the Healdton area, showing relation of Healdton to adjacent folds. After Powers, S.: A. I. M. E. Trans., Vol. LIX, p. 575, 1918.

---

[1] Data on Healdton mainly from:

Bartram, John G., and Roark, Louis: The Healdton Field, Oklahoma, A. A. P. G. Bull., Vol. 5, pp. 469–474, 1921.

Powers, Sidney: The Healdton Oil Field, Oklahoma, Econ. Geol., Vol. 12, pp. 594–606, 1917; also Age of the Oil in Southern Oklahoma Fields, A. I. M. E. Trans., Vol. 59, pp. 564–575, 1918.

Wegemann, C. H., and Heald, K. C.: The Healdton oil field, Carter County, Okla., U. S. G. S. Bull. 621, pp. 13–30, 1916.

well was completed in 1913. The productive horizons were found at shallow depths. The pool was expanded as rapidly as marketing facilities could be developed to take care of the production despite the over-production arising from the development of Cushing pool at the same time. The marketed production in 1917, the crest year, amounted to 18,350,000 barrels.

The Healdton structure lies immediately south of the belt of folding which resulted in the development of the Quachita, Arbuckle, and Wichita Mountains. These mountain-building movements appear to have begun in Mississippian time and to have resulted in intense uplift and folding of the beds which had been deposited previously in the wide Mid-Continent geosyncline of Oklahoma and northern Texas. Massive limestones and other strata, largely of Ordovician age, were arched up into a series of folds of varying size. Erosion of these uplifted areas tended to alter them greatly; and, as the period of erosion was followed by subsidence, they became irregular island areas in the great Late Paleozoic Mid-Continent sea. Deposition above and around them naturally followed. Where the masses were large and their flanks of moderate slope, the deposition resembled that along any normal shore. Where the uplifted areas were less extensive, as might be expected of folds and fault scarps some distance from the main areas of uplift, the subsidence carried the higher points to sea level and even below it.

A submerged reef having an anticlinal form is considered by Sidney Powers to have been an important factor in the accumulation of oil at Healdton. Although some oil has been taken from the Ordovician limestones, which represent the remains of such a reef, chief interest lies in the Pennsylvanian horizons, which overlie the Ordovician. The strata at the surface are Permian. They have a thickness of 200 to 800 feet depending upon topographic and geologic conditions. They have yielded some oil but have not been considered as of major importance.

The Permian rests conformably upon a body of Pennsylvanian blue shale from 300 to 450 feet thick. Below this lies the main oil zone, a series of interbedded shales and sandstones with thin limestones. It is from 250 to 350 feet thick and contains from two to five distinct sands depending upon the location. Beneath this zone is a body of Pennsylvanian rocks consisting mainly of blue shales but containing some oil and gas sands, water sands, and thin limestones. This zone is only 50 feet thick at the crest of the structure but thickens rapidly to the south where more than 500 feet have been measured. Below these beds lies a thin irregularly scattered deposit of limestone pebbles. It is known as the Frank conglomerate and represents the erosion surface of the Viola limestone of the Ordovician.

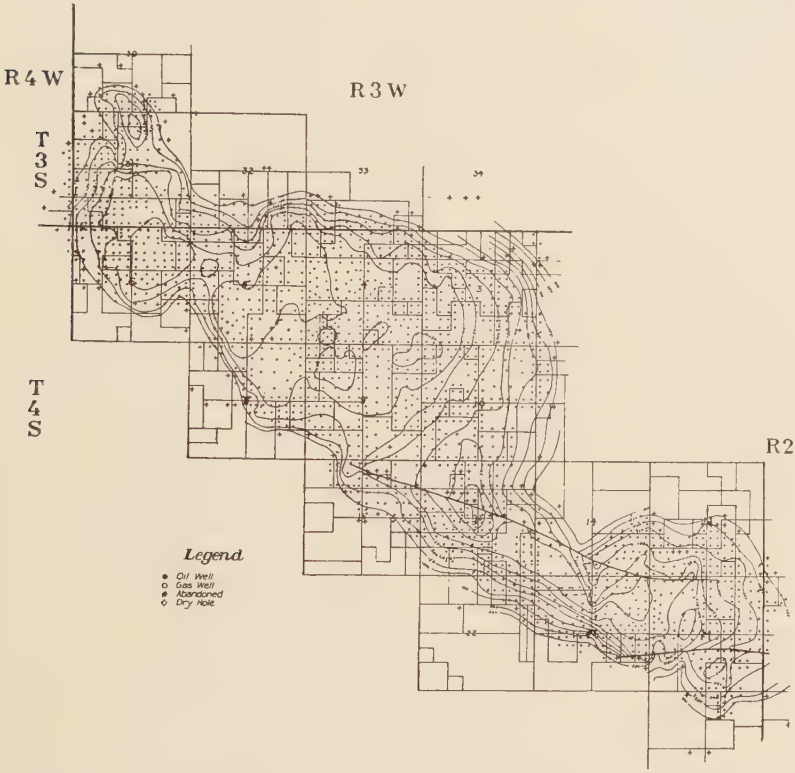


FIG. 144.—Subsurface contour map of the Healdton pool, Oklahoma. Contours on the top of the Healdton sand zone, interval 50 feet. After Bartram, J. G., and Roark, L.: A. A. P. G. Bull., Vol. 5, p. 472, 1921.

Accumulation in the different beds is naturally complicated. First, the individual beds are lenticular as a result of their deposition upon the flanks and above the highly eroded surface of the water-covered reef. Secondly, they have been tilted through differential compacting. Lastly, they have been subjected to a renewal of the orogenic movements that caused the initial uplift and folding of the area. The main period of subsequent folding was the latter portion of the Permian, but it is possible that there was some uplift during the early Permian and even during the Pennsylvanian. In all of these later movements differences in the thickness of the incompetent overlying strata and in the position of the surface of the covered competent beds were factors of importance. The area in which oil has accumulated is characterized by domes and saddles of small size. These do not appear to be common in the areas farther away from the centers of the covered peaks as shown by the drill.

The location of the Healdton structure is shown rather definitely in the overlying Permian. However, dips do not have the same steepness as those in the lower portion of the Pennsylvanian. Less is known about the character of the underlying Ordovician.

Robberson Pool, Oklahoma.[1]—The Robberson pool in Garvin County, Oklahoma, presents some points of similarity to the Healdton pool. This pool lies north of the belt of folding of the Wichita and Arbuckle Mountains. It was opened up in 1920 by the drilling of a small gas well. Later larger gas wells were completed; and in July, 1921, the discovery of oil was made. Two of the oil wells drilled had initial productions of more than 8,000 barrels daily. The average production was much smaller than this, however, and the decline of the wells especially rapid. As a result the pool has not been one of major importance although a substantial producer.

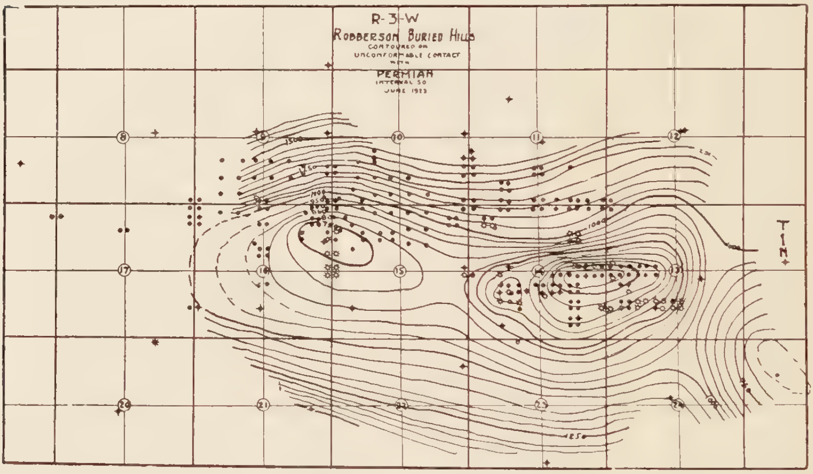


Fig. 145.—Subsurface contours on the surface of the "Robberson Hills." Contours in depths below sea level, interval fifty feet. After Denison, A. R.: A. A. P. G. Bull., Vol. 7, p. 632, 1923.

---

[1] Data from: Denison, A. R.: The Robberson Field, Garvin Co., Okla., A. A. P. G. Bull., Vol. 7, pp. 625–644, 1923.

The productive area is one that is marked by scarce and unsatisfactory exposures of outcrops. The only agreement between geologists who have worked over the surface has been with regard to the existence of an abnormal south and southwest dip. As the normal dip of the area is toward the north, this was considered as sufficient to warrant the starting of a test hole. The change in dip was found to coincide with the axis of the fold.

The first wells completed obtained production from a lenticular sand horizon in the Permian. According to Denison, the lenticularity makes it possible to contour only by the use of the upper surface of this producing horizon as a marker. The map produced in this way, however, gives adequate indication of the existence of an anticlinal fold and shows also the presence of typical domes and saddles. The sands contained in the horizon appear to contain no water, but gas is found in the normal relation.

None of the producers in this zone yielded more than 250 barrels daily. In 1922 a well was drilled through the Permian sand horizon into an underlying partly crystalline sandy limestone. It gave a yield of more than 1,000 barrels a day. The horizon was penetrated by other wells and found to be entirely different in character and structure from the Permian zone above it. The oil contained was under high pressure and was intimately mixed with water in some of the wells. In fact a number yielded an oil-water emulsion, which proved to be difficult to break down. The Pre-Permian horizon has a definite and regular north dip. To the south of it igneous rock has been found. A map drawn upon the contact of the Permian beds and the underlying mass, generally considered as of Ordovician age, shows much the same general outline as that of the contour map of the Permian producing horizon.

Analysis of the data presented suggests that a contour map of contact zone is the topographic contour map of a Pre-Permian hill which was buried beneath Permian deposits. The absence of wells other than a few inconsequential producers to the south side of the fold, together with the marked lenticularity and "gravelly" nature of the beds to the north, indicates the existence of near shore conditions of deposit. The position of the oil also points to accumulation from the north rather than from the south.

Part of the similarity between the Permian structure and the Pre-Permian topography may be traced to differential settling. It would appear that there have been some movements in the underlying base in addition, probably at the close of the Permian.

The oil contained in the Pre-Permian horizons comes from points varying from four to 402 feet below the base of the Permian. The subsea level of the producing section varies in different wells. There is no definite knowledge as to whether the oil comes from a single stratum. Several shows of oil have been found at varying depths. Wells have obtained oil from both porous crystalline limestones and from quartzitic sands. It would appear that all of the oil obtained below the unconformity had a common origin. However, the close proximity of large and small wells and the wide differences in the type of material containing the oil suggest a highly fractured and folded body of rocks. In addition the rocks were probably dissolved considerably by water action prior to their burial.

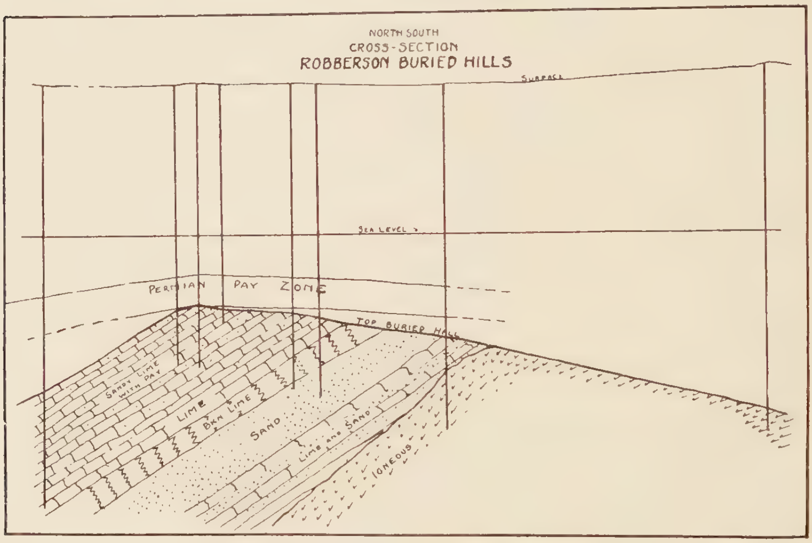


Fig. 146.—Diagrammatic cross-section showing attitude of beds in and above the "Robberson Hills." After Denison, A. R.: A. A. P. G. Bull., Vol. 7, p. 633, 1923.

Panhandle Structure, West Texas.[1]—The Panhandle district of the extreme northwestern portion of the state of Texas is one of the most important of the recent developments in oil production. Gas was discovered in Potter County in 1918. A number of large gas wells were drilled in the years following, but the distance of the district from any markets of sufficient size to warrant the cost of pipe lines tended to restrict the interest. In May 1921, oil was discovered in Carson County. Even then development was slow. The area was some distance from any refineries and had no pipe line connections. While other factors tended to keep interest down, the inability to comprehend the immense importance of the discovery was probably mainly responsible for the failure of operators to begin immediate development. The completion of several large wells in 1925 greatly increased interest in the area. Drilling began on a large scale. In 1926, 683 wells were completed, of which only 30 were dry. The production reached the total of more than 24,000,000 barrels for that year. Activities were curtailed somewhat in 1927 because of the low prices of oil, but a considerable area remains to be tested.

---

[1] Data mainly from:

Bauer, C. Max: Oil and Gas Fields of the Texas Panhandle, A. A. P. G. Bull., Vol. 10, pp. 733–746, 1926.

Pratt, Wallace E.: Oil and Gas in the Texas Panhandle, A. A. P. G. Bull., Vol. 7, pp. 237–246, 1923.

The importance of the area to the geologist lies first, in its size, and secondly, in the nature of the conditions under which the oil is found. The anticlinal structure is known to carry gas along its crest for a distance of over 90 miles. Oil has been found north of the axis at several points and one place to the south. Neither the extent of the oil area nor that of the gas have been outlined more than roughly. There is evidence to indicate that additional areas in the Panhandle section of Oklahoma may also be found to contain oil and gas in large quantities.

The wells yielding oil average about 2,900 to 3,100 feet in depth. The first 800 feet encountered in drilling consist of red sandstone, red shale, and gypsum. From 800 to 1,800 is largely salt interbedded with gypsum and red-beds. From 1,800 to 2,100 there are red-beds interbedded with thin limestones and streaks of anhydrite. Below this there are 800 feet of limestone, shale, dolomite, and anhydrite beds. These vary in color from blue through grays to white. Below 2,900 feet, or at a somewhat greater depth depending upon the surface topography and structural conditions, the wells enter a shaly layer with streaks of lime and anhydrite. Immediately below this, wells near the axis of the structure enter what has been called "granite wash." This is made up of arkosic sands. It consists of sharply angular fragments of quartz and feldspar with minor amounts

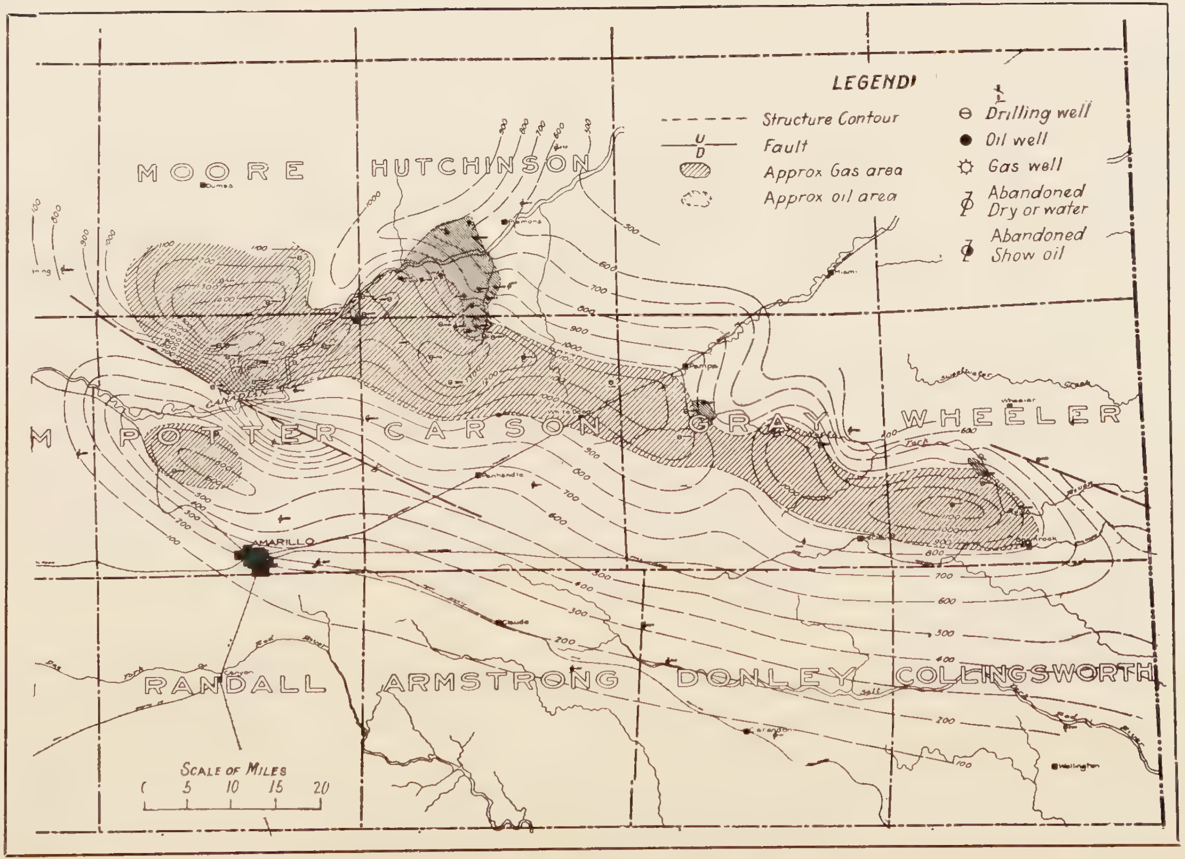


FIG. 147.—Structure map of the Panhandle oil and gas area. After Bauer, C. M.: A. A. P. G. Bull., Vol. 10, p. 735, 1926.

of hornblende and other minerals. With this are small bodies of red and blue shales.

The arkosic sand varies from a few feet in thickness at the tops of the domed areas along the axis to 250 feet or more on the flanks. It rests upon fresh crystalline igneous or metamorphic rock in the domed areas. In the basinal embayment areas, it reaches its maximum thickness. In a number of wells drilled between four and five miles from the high points of the ridges as disclosed by the drill, the granite wash is apparently missing. The surface of the granite wash is not conformable with the shale and lime series above it. As the edge of the granite wash is reached, the thickness of the overlying beds is increased by the presence of limestone between the shale and the wash.

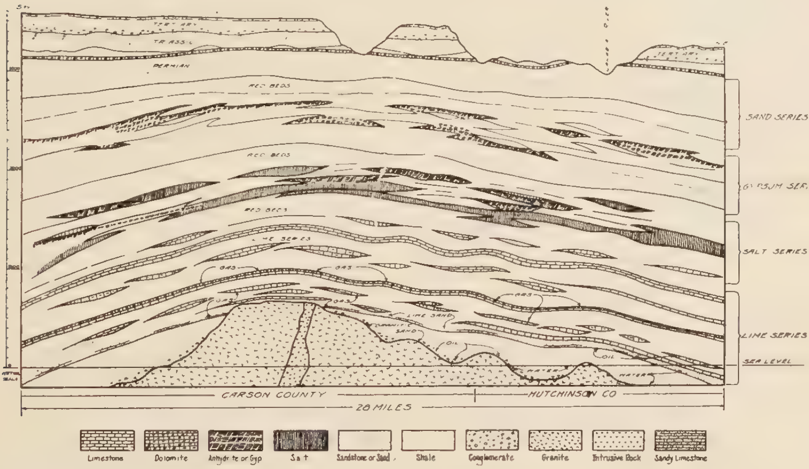


FIG. 148.—Ideal cross-section of the Panhandle structure. After Bauer, C. M.: A. A. P. G. Bull., Vol. 10, p. 737, 1926.

Some of the wells on the flanks have drilled through the wash and encountered limestones, black shales, and even coals beneath.

The structure of the area as shown by the outcropping beds is that of a major anticline. Contours of the surface beds, the only prominent one being the Alibates dolomite, show domed areas corresponding to the high spots on the underlying crystalline masses. They do not, however, reflect the exact slope of crystalline masses or the contours drawn on the lime horizon immediately above them. Two major faults are known. One lies to the south of the main axis. It has a throw to the southwest of 1,400 feet in the Lower Permian. South of this there is a subordinate uplift roughly parallel to the main one. The second fault lies northeast of the major fold. Its throw is to the northeast and it measures 1,000 feet in the Lower Permian. Both faults die out toward the surface.

The oil and gas are found in both the "Big Lime" series and the granite wash. The granitic sands are coarse, carrying pebbles as large as peas and in some places even boulders. They appear to be stream or talus deposits that have been reworked to some extent by the waters of Permian seas. The portion of the limestone that yields oil is really a dolomite. It is frequently high in anhydrite also. The porous portion of the limestone is about 200 feet in thickness and contains several layers of from 15 to 30 feet thickness, which have sufficient porosity to contain oil. One of these is oölitic, while another contains vesicular openings.

The gas occurs at depths of from 1,600 to 2,400 feet along the crest of the structure down to 2,900 feet on the flanks. The first gas is found about 320 feet below the top of the Big Lime and at various intervals from there down for 500 feet. The oil lies in a horizontal belt whose upper limit is about 200 feet above sea level and whose lower limit is at or within 20 feet of sea level.

The water level is considered to be a static one as it is practically the same throughout all of the district. Similarly the gas pressure ranges from 420 to 460 pounds per square inch throughout the whole area. This figure is considerably lower than would normally be expected at such depths. One of the interesting features is that the gas pressure is the same regardless of the source, whether in the granite wash or in the dolomite.

The gas-containing area was opened in 1918. The proved area early in 1926 was considered to include 325 square miles. Considerable gas had been used and much lost through inability to control some of the wells, but no decline in pressure had been noted. The oil is of 34 to 37° Baume but differs from other Paleozoic oils in congealing at the unusually high temperature of 50° F.

It has been suggested that the arching of the beds above the granitic masses is the result of differential settling. The intense throw of the known faults and the high dips and closure on the limestone beds would make this doubtful from a quantitative standpoint if from no other. It seems more probable that the structure is the result of direct uplift along the axis of an older topographic feature.

The extent of the area affected and the amount of the vertical uplift would naturally give rise to the development of faults and folds. If the result of a series of uplifts, it would result in folding of the upper beds similar to the folds in the lower but smaller in intensity.

Gemsah and Hurghada, Egypt.[1]—Two of the producing pools in Egypt yield oil from structures that are known to be connected with buried granite masses. These are the pools at Gemsah and Hurghada. Several wells at Gebel Zeit, a minor producing section, have produced oil from points adjoining outcropping granite. The Gemsah pool is the less important of the larger pair. The wells have been of large initial capacity, one completed in 1914 yielding 20,000 barrels a day. The decline in all cases was rapid, the wells going to water. This apparently came in through a highly porous, fissured rock. The reservoir rock has been identified as a coral reef dolomite. The coral reef appears to have grown upon the top and sides of a granite mass. It probably formed a coral island in the Miocene sea. So far, production has been restricted to the coral area.

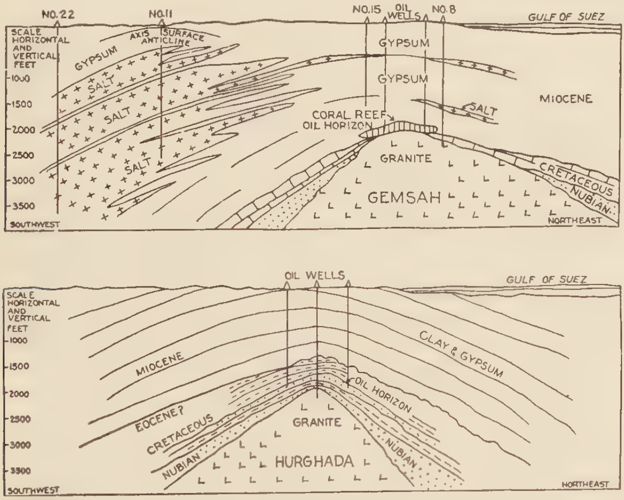


Fig. 149.—Cross-sections of the Gemsah and Hurghada oil pools, Egypt. After Powers, S.: A. A. P. G. Bull., Vol. 10, pp. 436 and 438, 1926.

---

[1] Data mainly from:

Hume, W. F.: Report on the Oilfields Region of Egypt, Ministry of Finance, Cairo, 1916; also The Geology of the Egyptian Oil-field, Inst. Pet. Tech. Jour., Vol. 7, 394–417, 1921.

Powers, Sidney: Reflected Buried Hills in the Oil Fields of Persia, Egypt, and Mexico, A. A. P. G. Bull., Vol. 10, pp. 422–442, 1926.

TABLE 60.—COLUMNAR SECTION OF THE EGYPTIAN OIL AREA.*

Recent.			Gravels and coral reefs.
Pleistocene.	Pecten series. Laganum series.		Coral limestones with living and extinct fauna, gravels with igneous pebbles.
Pliocene.			Limestones and oyster beds with *Ostrea Gigensis* and *Ostrea Virlete.* Calcareous sandstones often oolitic with *Tellina Lacunosa* and Venus. Dolomitic limestones. Massive fetid limestones and gravels with flint pebbles, no igneous.
Miocene.	Upper.		Massive gypsum beds and gypsum-clay series over a gypsum-salt or rock-salt series.
	Middle.		Dolomitic limestones with fetid odour and sulphur.
	Lower.		Globigerina marls and fish-scale beds with oil traces, dark limestones and dolomites.
			Basal conglomerate composed of flint and limestone pebbles.
			Unconformity.
Eocene.	Upper.	Red marls.	Vivid red and purple marls and clays, sometimes only yellow. Especially brilliant when in contact with basaltic intrusions.
		Gypseous marls.	Yellowish or dark gypseous and salty shales of mud or clay. Sometimes a clayey limestone.
		Green beds.	Green[1] and brown gypseous marls and dark yellow limestones. White marly, chalky limestones with some flint bands and fish teeth.
	Lower.	Cardita limestone.	Chalky marls—limestones in upper part with many flint bands, decreasing towards base—highly gypseous, often darkened by impregnation with hydrocarbons, especially near volcanic dykes.
		Nummulitic (scarp) limestone.	Hard crystalline limestones and chalky gypseous marls, no flints but nummulites.
Cretaceous.	Esna shales (Mæstrichtian).		Deep-sea marls and marly limestones.
	Senonian (Campanian and Santonian)		Limestones and phosphate[2] beds with shark's teeth. Shallower water sandy at times.
	Cenomanian.		Limestones with *Ostrea exogyræ.* Here limestones replace lower sandy phase.
	Nubian.		Highly quartzose, false-bedded sandstones with many white quartz pebbles, calcareous in upper layers and shales.
Ancient.			Granites and porphyries with dykes of diabase and felsites.

[1] Color derived from glauconite and sulphates.

[2] Source of commercial supplies of phosphates.

* After Thompson, A. B.: Oilfield Exploration and Development, Vol. 1, pp. 496–497, 1925.

The bulk of Egypt's production of more than a million barrels a year has come from Hurghada pool, about 31 miles southeast of Gemsah. The outcropping Miocene beds, consisting largely of clays and gypsum, have been folded in the form of an anticline. They rest unconformably upon sandy shales in the Upper Cretaceous. These are apparently conformable with the underlying Nubian sandstone, but the latter rest upon a brecciated and weathered granite surface. The oil was found in the Upper Cretaceous sandy shales, in the Nubian sandstone, and in the porous weathered surface of the underlying granite. It has been noted that the dips on the Cretaceous and the Nubian horizons are greater than those of the Miocene beds above them.

The data indicate that the granitic core was an area of emergence and has been the center of uplift at various times during the periods in which sedimentation was taking place.

Maidan-I-Naftun, Persia.[1]—Practically all of the oil produced up to the present time in Persia has come from the Maidan-I-Naftun structure in southwestern Persia. Geologic work was started here in 1894, but the first commercially productive well was not completed until 1908. Since then the development has been steady, the production of the area reaching 35,000,000 barrels in 1925. A larger total probably could have been obtained had there been a market for it. The producing horizon is similar to that of Mexico, a highly porous dolomitized and cavernous limestone. It forms the upper eroded portion of the Asmari limestone. Part of the horizon may be considered to be a weathered but not transported portion of the Asmari, but much of it is probably a detrital limestone made by reworking the disintegrated Asmari beds.

The producing fold has not been fully outlined although the number of producing wells is now large; and the amount of oil taken out, great. The general axis of the anticline is northwest-southeast. Over the main area of the fold, the Lower Fars or gypseous series is exposed. The northwest slope is apparently gentle and fairly regular, but the southeastern flank is steeper and largely obscured by a thrust fault. The main anticline shows a complicated system of minor folds upon the surface. In the central part of the structure, these minor folds are simple and open in type. To the southeast they become more compressed, changing into isoclinal and recumbent folds.

---

[1] Data mainly from:

Busk, H. G., and Mayo, H. T.: Some Notes on the Geology of the Persian Oilfields, Inst. Pet. Tech. Jour., Vol. 4, pp. 3–33, 1918.

Richardson, R. K.: The Geology and Oil Measures of South-West Persia, Inst. Pet. Tech. Jour., Vol. 10, pp. 256–296, 1924.

They contain minor reverse faults, which culminate in the Tembi thrust fault.

The minor flexures in the Fars series do not appear to be reflected in the broad structure of the Asmari below. The explanation of this condition lies probably in the difference in the competency of the Fars and the underlying more massive Asmari and older limestones.

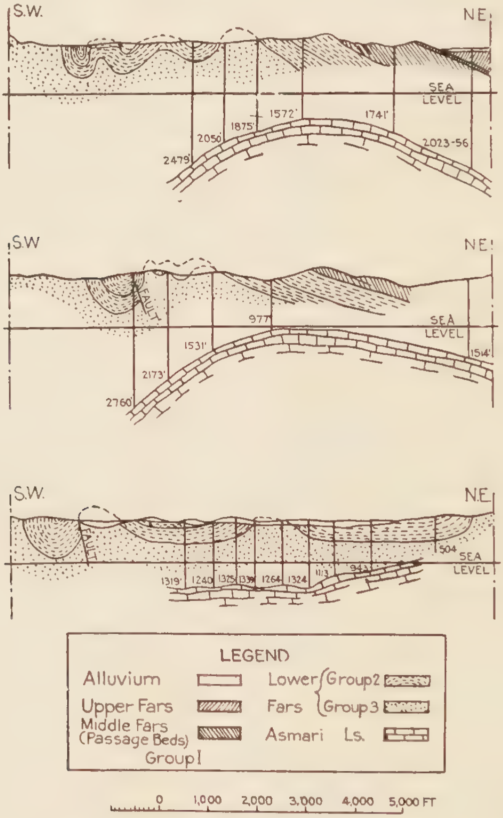


FIG. 150.—Cross-sections through the Maidan-I-Naftun structure, Southwestern Persia. After Richardson, R. K.: Inst. Pet. Tech. Jour., Vol. 10, p. 278, 1924.

There has been some tendency to think of this as a structure comparable to those in southern Oklahoma, which have just been discussed. Undoubtedly there was a period of uplift accompanied by some folding at the close of the deposition of the Asmari and prior to the deposition of the overlying beds.

Richardson[1] has pointed out, however, that the junction between the two groups at their outcrop is conformable. There is evidence of a gradual overlap accompanying moderate tilting of the lower beds. The contact between the limestone and the gypseous series offers a good chance for the development of slip planes and has probably made movements along that contact comparatively easy.

The history of structural movement in this area is bound up with the great Himalayan uplift of Tertiary time. The Bakhtiari Mountain folds to the northeast of the producing structure are roughly parallel to it. They are much more marked because of nearness to the thrust center. In the Maidan-I-Naftun and other folds, the covering of plastic Fars beds has reacted to the intense thrust transmitted through the more competent limestones in a manner typical of incompetent beds under a limited amount of covering. The following interpretation of the geologic history as given by Richardson[2] seems to be a logical explanation of the structural conditions now present.

Asmari Period—During which a great thickness of massive limestone was laid down.

1st Phase of the Himalayan Movement—Initiation of earth movement.

Fars Period—A period of relative quiescence during which slight and gradual uplift—a continuation of the initial earth movement—may have occurred. Argillaceous deposits and chemical precipitates were laid down under conditions of intense desiccation believed to end when the older Fars rocks were laid down.

2d Phase of Himalayan Upheaval—Commencement of the first big upheaval, which continued throughout Bakhtiari times.

Bakhtiari Period—During which the conglomerates and sands of non-marine origin were laid down under continued earth movement.

3d Phase of Himalayan Upheaval—Final grand upheaval at the close of Bakhtiari Period.

Pleistocene and recent deposits.

The Granite Ridge of Kansas.—The granite ridges or buried Nemaha Mountains of Kansas are the outstanding feature of the westward sloping monocline of eastern Kansas. The main ridge extends southward from Nebraska in a southerly direction through Kansas. In southern Nebraska it lies within 500 feet of the surface.

---

[1] Idem, p. 281.

[2] Idem, p. 275.

In the Augusta pool of Kansas, it was reached at 2,865 feet. Similar ridges have been located in a general way to the east and west of the main one. The main ridge is known to have been emergent throughout much of the Mississippian and the Early Pennsylvanian. In the southern part of Kansas, the granite did not show at the surface but was overlaid by arched Ordovician or other Pre-Mississippian rocks. The granite ridges also extend southward into Oklahoma. Here they are more deeply buried, especially toward the western portion of the producing areas. At Cushing granite was found at 3,670 feet. The

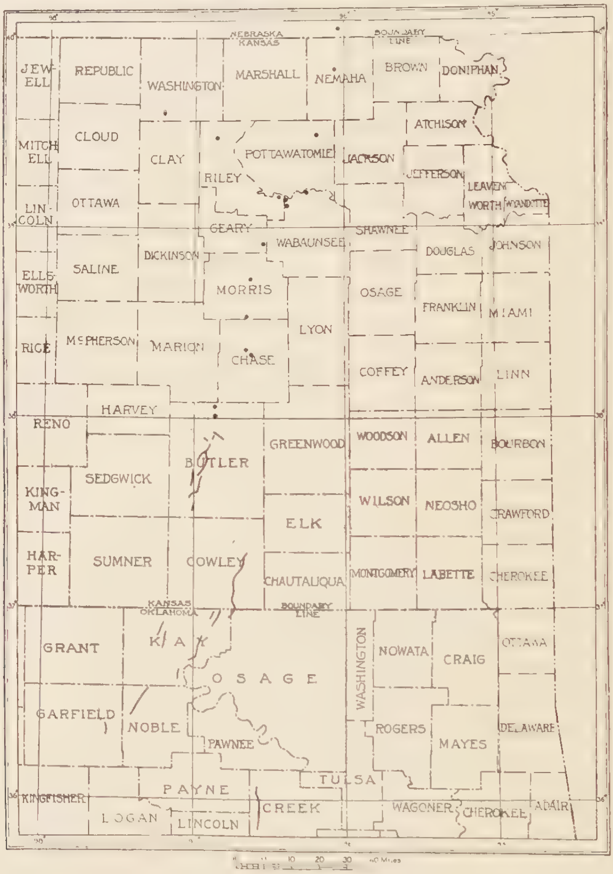


Fig. 151.—Sketch map of Eastern Kansas and Northeastern Oklahoma showing distribution of "Granite Wells" (black dots) and several extensive anticlinal folds (heavy black lines). After Fath, A. E.: U. S. G. S. Prof. Paper 128, Plate XIV, 1920.

importance of the granite ridge of Kansas, about which most is known, is that it served at least partly to divide the Mississippian and Early Pennsylvanian seas of the Mid-Continent area and to promote sand deposition along its flanks. In addition, it was a continuously positive element tending to rise and arch the strata above it.

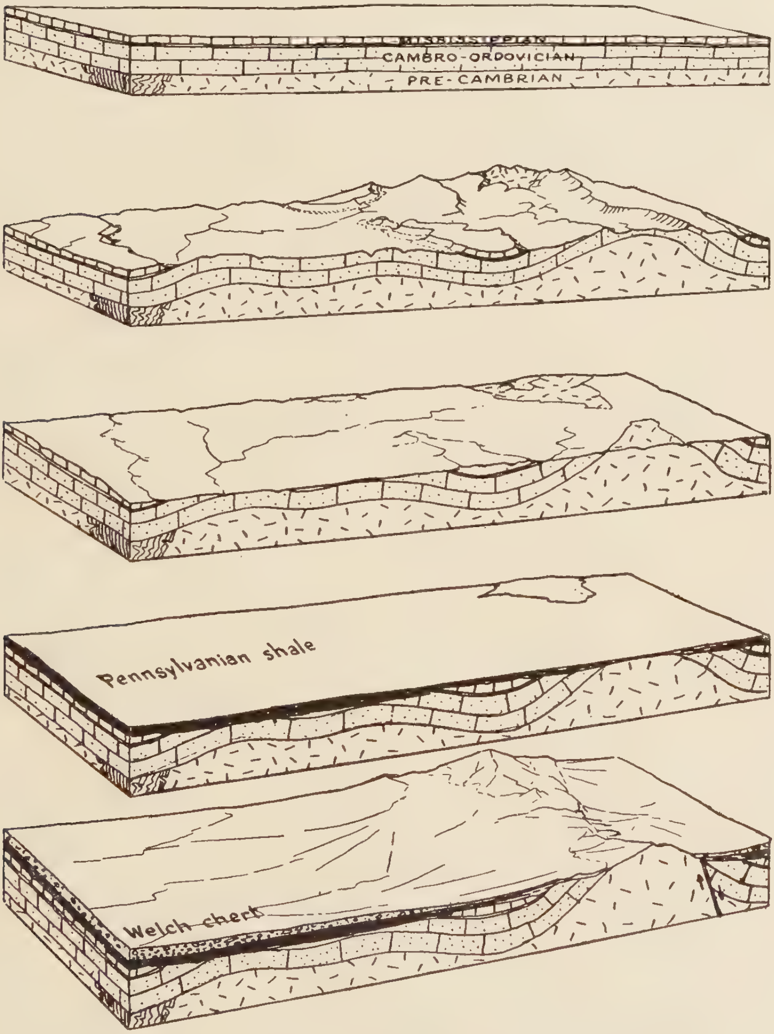


FIG. 152.—Diagrams representing successive stages in the inferred history of the Nemaha Granite Ridge, east central Kansas. After Moore, R. C.: A. A. P. G. Bull., Vol. 10, p. 211, 1926.

Eldorado and Augusta, Kansas.[1]—The first recognition of the importance of the granite ridges came with the development of two large pools in Kansas, the Eldorado and the Augusta pools. The first is immediately north of the second. The exposed formations are of Permian age. Beneath the Permian lie upper and middle Pennsylvanian. Except for a very small portion of the Cherokee formation, all of the lower Pennsylvanian appears to be absent in the area of the pools. Similarly, the Mississippian, Devonian, and Silurian are all absent, the Pennsylvanian resting directly upon the Ordovician. The top of the Ordovician represents the old land surface of a truncated anticline. Cherty limestone is shown by the drill to mark the highest portion of the anticline in the Ordovician. On the flanks remnants of an overlying sandstone of Pre-Pennsylvanian age occur. Below the Ordovician cherty limestone the drill found a series of massive limestones overlying a granite surface.

Oil has been taken from horizons known as the 500-, 700-, 1,700-, 2,000-, and 2,500-foot sands. An important stray sand was found 75 feet above the 1,700-foot horizon, and gas has been found in sands reached at 900, 1,125, and 1,475 feet. The upper sands are lenticular and are limited to parts of the structure. The 1,700- and 2,000-foot horizons are lime sands. While continuous, their production was restricted to the domed areas of the structure. The 2,500-foot or Stapleton zone has proved to be the most important horizon in the pool. This zone represents the contact between the Pennsylvanian and the underlying eroded surface of the Ordovician. In the center of the structure, it is a porous cherty lime; and on the sides, a sand.

The Augusta structure is elongated along a definite axis, but the closure on the Eldorado is triangular in form. Within its main structure are a number of small domes, locally known as the Shumway, Bayer, Oak Hill, Chesney, and the Wilson. The closure on the surface rocks is 180 feet, but that on the Stapleton zone is 450 feet. The difference in closure on the beds between these extremes increases steadily with depth.

While part of the closure on the Stapleton may be attributed to Pre-Pennsylvanian erosion, the bulk should be attributed to Pennsylvanian and Permian folding. Decrease in the intensity of the folding with approach toward the surface is considered to be largely due to the continuous nature of the movement causing the folding. It could

---

[1] Data mainly from Fath, A. E.: Geology of the Eldorado Oil and Gas Field, Butler County, Kansas, State Geological Survey of Kansas, Bull. No. 7, 1921.

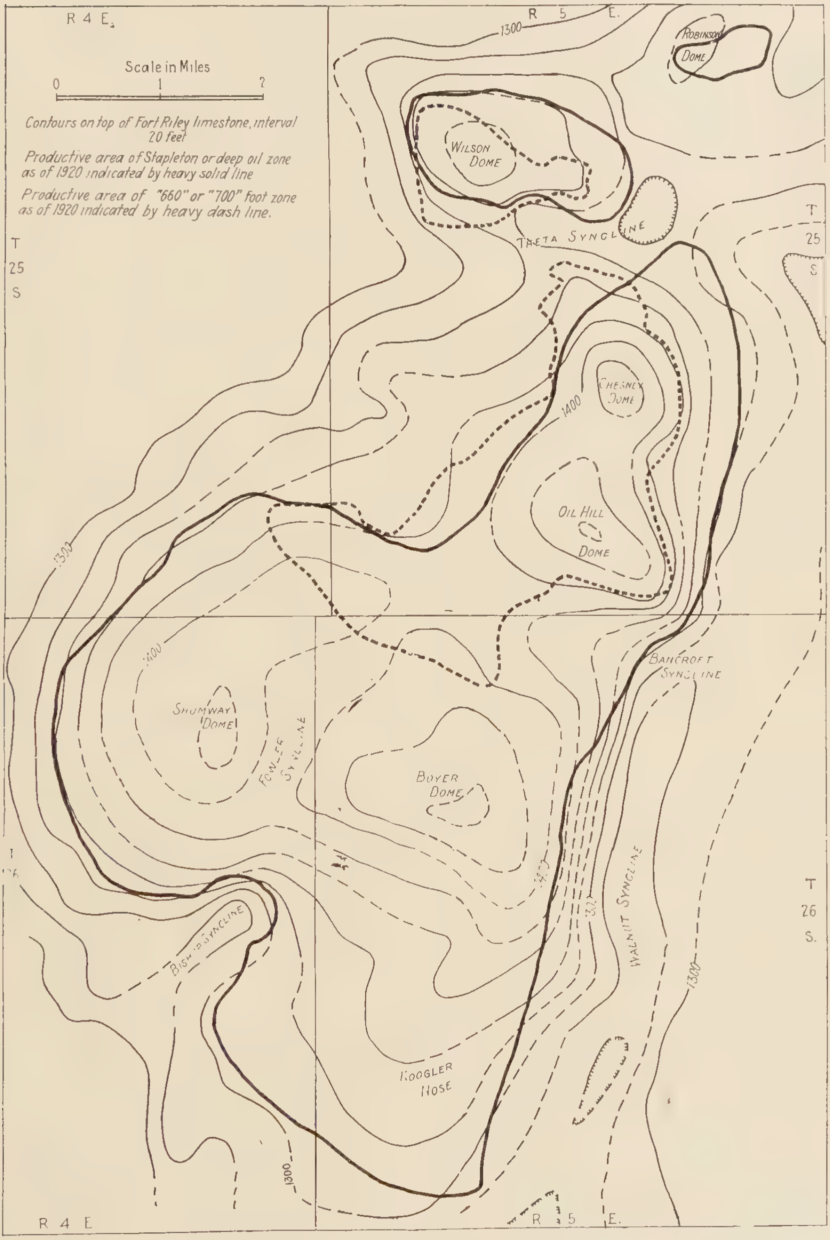


Fig. 153.—Outline structure map of the El Dorado pool. Adapted from Fath, A. E.: State Geological Survey of Kansas, Bull. 7, Plate XIV, 1921.

hardly be considered as due to differences in the amount of sediments laid down upon the old erosion surface, as it persists in the upper horizons as well as the lower ones. The amount of the increase in closure on three of the domes at El Dorado has been shown by A. E. Fath[1] to be as follows:

	Wilson Dome	Chesney Dome	Oil Hill Dome
Surface rocks..................	40 feet	20 feet	30 feet
660 foot sand (700)............	60+ "	40 "	50 "
Stapleton sand (2400)..........	100+ "	80+ "	80 "

Cushing, Oklahoma.[2]—The Augusta-El Dorado area was opened up in 1916. The existence of the marked unconformity was recognized early and the presence of granite proved by the drill in Augusta in 1918. Practically the whole of the development of Cushing was completed before the finding of granite and the realization of the existence of a deep productive unconformity.

This famous pool was discovered in 1912, when production was developed in the Wheeler and Layton sands at 2,100 and 1,400 feet, respectively. Both of these sands were substantial producers but were not productive of the yields that later caused Cushing to dominate the petroleum industry of the world. In December of 1913, the pool appeared to be on the decline, when a 2,000-barrel well was completed at 2,600 feet. This horizon was called the Bartlesville by the drillers because of its relationship to the overlying beds. Production from this horizon was increased rapidly by the drilling of a large number of wells, the yield going above 300,000 barrels a day in 1915. The production for that year reached a total of 70,000,000 barrels, or one-quarter of the total production of the country. In 1921 a deep test found granite at 3,670 feet in the center of the Shamrock dome. After this came a gradual realization of the complicated character of the deeper structure. This realization has been supported by later data.

The Cushing structure is one of the best known examples of an anticlinal fold crossed by producing saddles. On this fold there are five definite domes and four saddles. The largest of the domes is the

[1] U. S. G. S. Prof. Paper, No. 128, p. 83.

[2] Data mainly from:

Beal, C. H.: Geologic Structure in the Cushing Oil and Gas Field, Okla., and Its Relations to the Oil, Gas and Water, U. S. G. S. Bull., No. 658, 1917.

Buttram, Frank: The Cushing Oil and Gas Field, Okla., Okla. Geol. Survey, Bull. No. 18, pp. 1–60, 1914.

Gardner, J. H.: Discussion in Pet. Dev. and Tech. in 1926, pp. 647–648.

northernmost or Dropright. Its crest is 100 feet higher structurally than the elevation of the Wheeler saddle immediately to the south of it, when contours are drawn upon the outcropping Pawhuska limestone. In the Layton sand, which lies about 1,450 feet below the Pawhuska, the closure on the Dropright dome is nearly 200 feet. The closure in the Wheeler sand is somewhat more and in the so-called Bartlesville is placed at nearly 250 feet. The Dropright dome was largely gas-covered in the Wheeler and the Lawton sands. In the latter the Wheeler saddle was an important source of oil. In the deeper Bartlesville horizon, the greater thickness of sand and the smaller quantity of gas have caused the oil and gas to be concentrated in the Dropright dome. The Wheeler saddle in this horizon contains only water.

South and a little east of the Wheeler saddle are the Drumright and Mount Pleasant domes separated by a narrow and comparatively shallow unnamed saddle. Gas is found in the Wheeler and the Layton in both the domes and the saddle area separating them. In the Bartlesville a little free gas was found in the domes, but they and the saddle are known mainly for their yield of oil.

The bulk of the oil of the Layton and Wheeler sands was found in a broad comparatively flat area

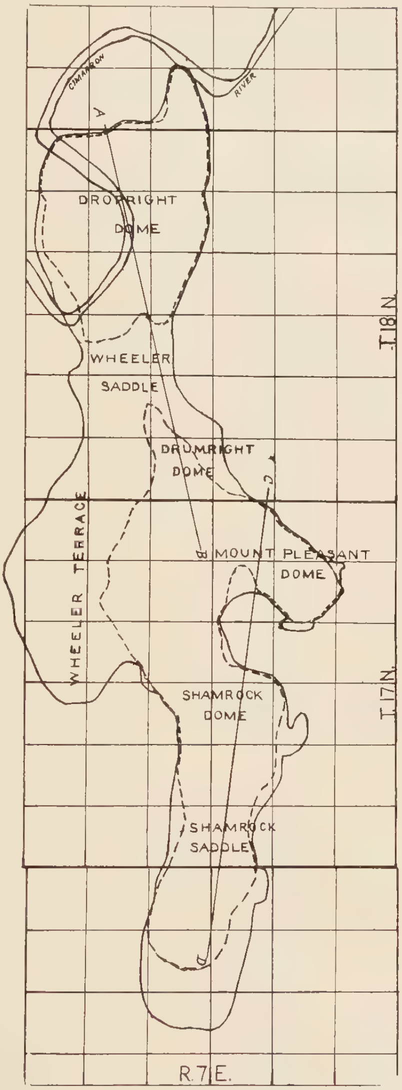


FIG. 154.—Sketch map showing position of producing areas of the Cushing pool. Heavy line indicates extent of productive area of the so-called "Bartlesville" horizon. Dash line indicates production in upper horizons. Adapted from maps by Beal, C. H.: U. S. G. S. Bull. 658, 1917.

to the southwest of the Drumright Dome, known as the Wheeler Terrace. The concentration of gas in these horizons in the eastern portion of the structure cannot be explained wholly by structural conditions, the edges of both oil and gas zones being higher structurally to the east than to the west. On the east, gas and water are practically in direct contact. This would indicate that in these upper horizons the movement of the oil and gas was from the west. The production of oil from the Bartlesville is limited to the slightly higher eastern portion of the terrace.

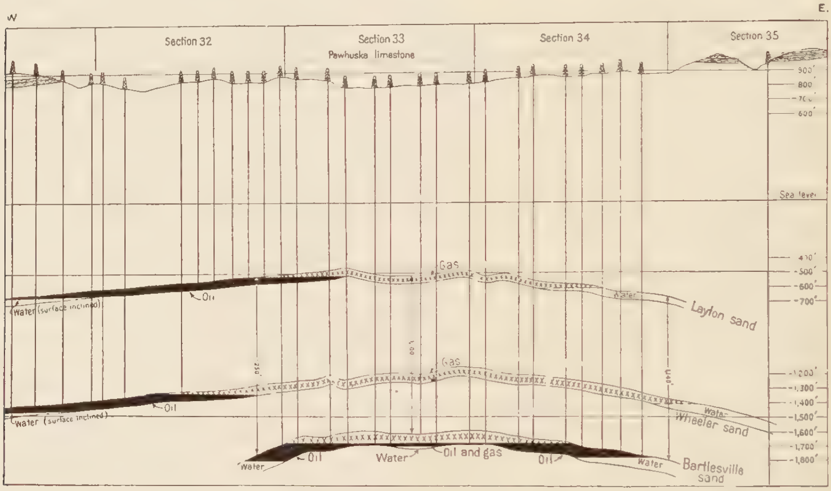


FIG. 155.—Sketch section along south line of T. 18 N., R. 7 E., through the Drumright dome, showing the stratigraphic relations of the Pawhuska limestone and the Layton, Wheeler and Bartlesville sands, the increase in the Layton-Bartlesville interval, and the inclination of the water surfaces. After Beal, C. H.: U. S. G. S. Bull. 658, p. 30, 1917.

Southeast of the flat terrace area is a dome known as the Shamrock. Except along its western edge, where some oil has been obtained, it is important only as a source of gas in the upper horizons. It is an important source of oil from the Bartlesville. South of the Shamrock dome the surface contours show no further irregularities along the southward dipping axis of the fold. The subsurface maps show the presence of a small domed area before the rapid dip starts. The slight depression between this unnamed dome and the Shamrock dome is known as the Shamrock saddle. The distribution of oil and gas in this section was much the same as it was in the area to the north.

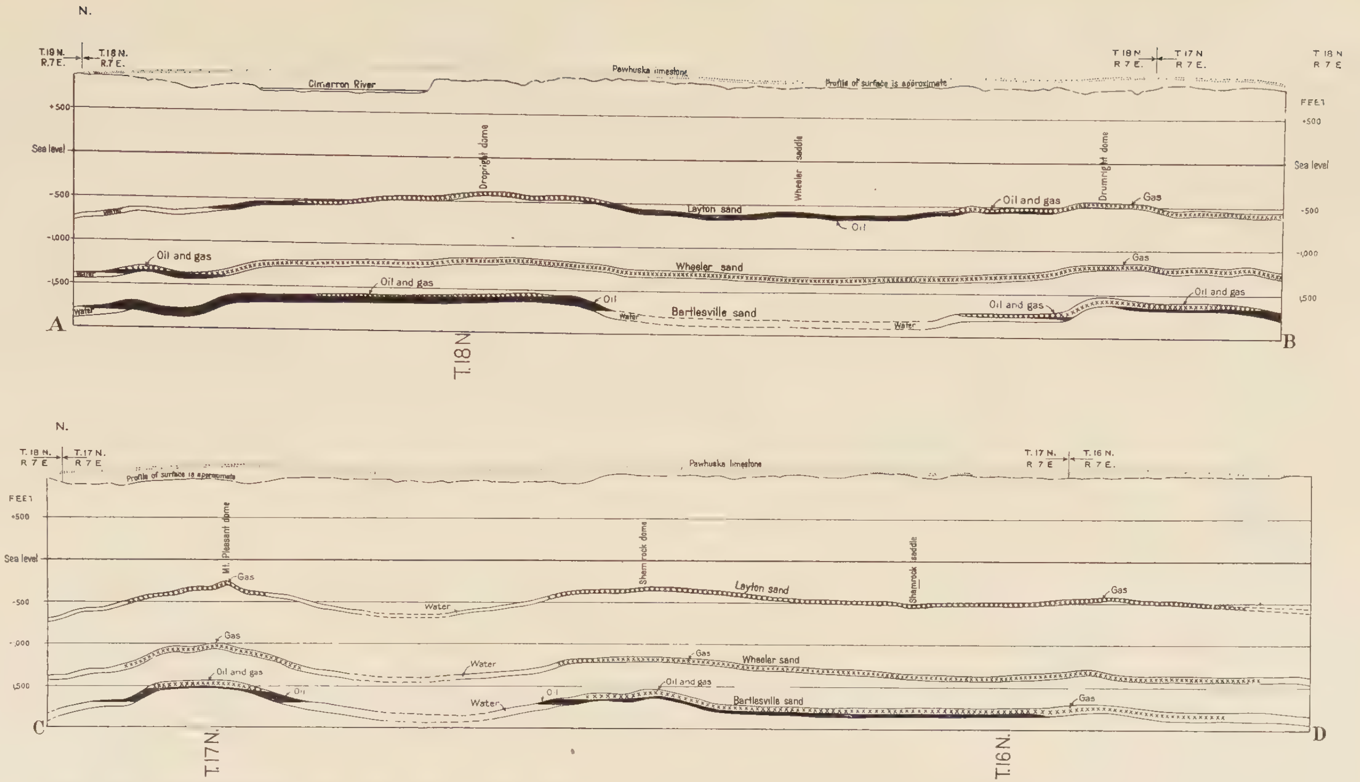


FIG. 156.—Cross-sections along the Axis of the Cushing structure. After Beal, C. H.: U. S. G. S. Bull. 658, Plate 5, 1917.

The closures on the other domes increase vertically with depth in somewhat the same manner as they do on the Dropright dome. Some irregularities have been noted in the rate of increase that tend to indicate that folding or uplift has not always occurred at the same place at the same time. These are noticed especially in the eastern portion of the area where the shallow horizons were mainly gas-producing. As these were penetrated during a mad scramble to reach the Bartlesville, the accuracy of the records may be questioned a little. The only assumption that appears warranted is that there is a steady downward vertical increase in the closure throughout the structure as a whole. On the average, the rate of increase appears to be greater between the surface beds and the Layton than below the latter. The condition indicated is one of slight folding or possibly merely compacting prior to one of more marked folding during the period following. Folding undoubtedly followed the period of later sedimentation and affected the area as a whole.

The Bartlesville has been discussed as if it were a single stratigraphic unit similar to the Layton and the Wheeler. This was assumed to be the case throughout all of the development period. It is now recognized that this is not true and that the greater portion of the production came from the Wilcox and siliceous lime horizons of Pre-Chattanooga age. The underlying formations were subjected to intense upfolding prior to the Pennsylvanian. The area formed by the uplift was then subjected to intense erosion, probably as much as 1,300 feet of sediments being removed from the center of the fold. Over the top and on the sides of the remains of the fold, the Cherokee shales were deposited during Early Pennsylvanian. In parts of the area, these appear to be in contact with the siliceous lime, in others with the Simpson and Wilcox sands. The true Bartlesville occurs off to the side of the structure.

Seminole District, Oklahoma.[1]—The first well in this famous Oklahoma district was completed on March 7, 1926. The oil was obtained from the Hunton lime, a formation which had produced relatively little oil in other parts of Oklahoma. In July of the same year two wells were completed which proved the existence of oil in the underlying Wilcox sand. As one of these was of the gusher type and as leases in the area were distributed among a large number of concerns, the development was rapid. The original discovery was named the Seminole City pool. Its production rose steadily, the peak being reached when a yield of 253,000 barrels daily was obtained late in February of 1927.

---

[1] Data mainly from:

Lovejoy, J. M.: The Seminole Oil Fields, Mining and Metallurgy, Vol. 8, pp. 348–350, 1927.

Powers, Sidney: The Seminole Uplift, Oklahoma, A. A. P. G. Bull., Vol. 11, pp. 1097–1108, 1927.

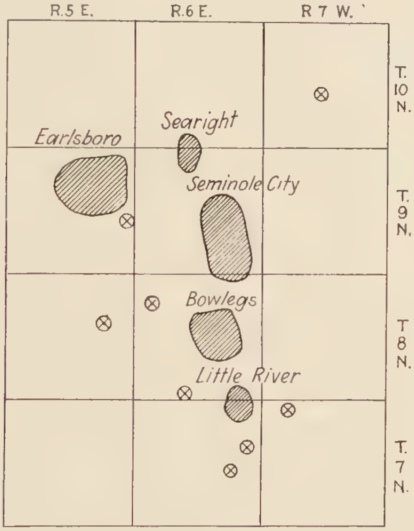


FIG. 157.—Sketch map of the Seminole District, showing developed pools and prospect wells producing under shut-down agreement as of January, 1928.

Late in 1926 equally sensational pools were discovered at Earlsboro and Bowlegs. Important but smaller pools were found at Searight and Little River. The former was discovered in October of 1926; and the latter, in July of 1927. Within twelve months after the discovery of oil in the Wilcox horizon the yield of the whole section reached a total of approximately 75,000,000 barrels. The crest production for the district came on July 30, 1927, when 527,000 barrels of oil were obtained. Practically all of this came from the Wilcox sand and averaged 40 degrees Baume in gravity.

The production fell below 400,000 barrels daily before the close of 1927. The decline was due in part to natural decline of the wells with decreasing gas pressure and in part to the rulings of a shut-down agreement which postponed the drilling of wells near tests which had demonstrated the existence of other pools in the district.

The surface beds in the area are of Pennsylvanian age. The normal dip is westward and the rate about seventy feet to the mile. The outcropping beds are not suited to accurate contouring. However, careful work on the surface has proven the presence of a number of anticlinal flexures of the nose type and of a series of small échelon faults. The latter are most pronounced in range six east. They have definite northwest to southeast strikes. The number of the faults together with the position of the area midway between the strong Cushing structure to the north and the Arbuckle Mountains to the south led to the conclusion that they were surface indications of pronounced folding in the deeply buried Pre-Pennsylvanian strata.

TABLE 61.—PRE-PENNSYLVANIAN PALEOZOIC HORIZONS IN THE SEMINOLE DISTRICT.*

Mississippian	Lower Caney—150 to 450 feet (Lower 20 to 200 feet called Mayes)—Dark brown to black shale, granular calcareous grit.
	Sycamore Lime—0 to 10 feet—Green, glauconitic shale and lime.
	Woodford (Chattanooga)—10 to 140 feet—Dense, brown to black pyritic shale, cherty at top.
	Misener Sand—0 to 15 feet—Irregular, round-frosted and subangular sandstone.
Devonian-Silurian	Hunton Lime—0 to 150 feet—White to pink crystalline limestone.
Silurian	Sylvan Shale—15 to 110 feet—Greenish gray to gray, fine grained, pyritic shale, often darker toward base.
	Viola Lime—20 to 70 feet—Coarsely crystalline, white and gray, sometimes pink.
Ordovician	Simpson Lithographic-Dolomitic Limestone—0 to 75 feet—Dense, buff to brown lime, imperfectly dolomitized, particularly sugary in texture toward base.
	First Wilcox Sand—70 to 125 feet—Irregular sized, round-frosted and subangular sand, limy.
	Second Dolomite and Green Shale—0 to 40 feet—Brown, sugary lime, may be sandy, and dark green shale.
	Second Wilcox Sand—Even grained, subangular sand—no lime, no shale.
	Simpson Sand and Green Shale—Uneven grained, round-frosted sand and dark green shale, not limy.

* Adapted from section prepared by Micropaleontological Society of Tulsa, O. & G. J., Feb. 2, 1928, p. 70.

The general accuracy of this conclusion was fully demonstrated by the discovery of the Seminole City pool. Beyond this it is not possible to make definite statements about the relationship between surface structure and the structure of the Ordovician beds. A majority of the discovery wells of the district were located on surface noses. However, a number of dry holes were located at points having similar surface structure. Noses in surface beds have been found to overlie synclinal as well as anticlinal parts of the productive horizon. All of the producing sections may be described as sharply defined anticlines in the Wilcox series. The shallowest production in the Wilcox is found at a subsea level of 2,950 feet, the deepest about 500 feet lower. Water under pressure marks the edges of production in all of the pools. Contours drawn on the Viola limestone, a definite marker horizon immediately above the Wilcox sand, show the deeper horizons to be folded into a number of minute close folds. Possibly faults of large throw but limited horizontal extent are also present. Differences in elevation in offset wells of 200 feet are not unusual.

A small amount of oil has been secured from the Earlsboro sand, a horizon in the lower part of the Pennsylvanian. This only faintly reflects the intense uplift and folding of the underlying Pre-Pennsylvanian rocks. A relatively thin section of Mississippian beds of variable thickness separates the base of the Pennsylvanian from the underlying eroded surface of the Hunton lime and the Sylvan shale of the Siluro-Devonian. The Mississippian beds have been folded more than the Pennsylvanian, but the major period of uplift appears to have occurred immediately after the deposition of the Hunton lime. The period of erosion immediately following the uplift removed a large part of the Hunton lime, particularly in the highest parts of the uplifts. Thus while the Hunton is frequently found to contain oil, the best locations from a structural standpoint are those where it is too thin to be an important producer. In these sections the Wilcox sands of the Simpson formation have served as excellent containers for the oil.

Tonkawa, Oklahoma.[1]—The prominent Tonkawa pool is located in Townships 24 and 25 North and Range 1 West in Kay and Noble Counties, Oklahoma. It is one of the most important pools that have been developed in the western portion of the North Mid-Continent area. The discovery well was completed in June, 1921, but the drilling of several dry holes near it indicated that the structure was likely to prove one of limited and spotty nature. Later operations disproved the early assumption, the original test being found to have been located on the extreme southern end of a terrace-like extension of the main structure. The development of the main pool began during the last part of 1922 and was carried on with great energy throughout 1923. The pool, together with Burbank, dominated the producing industry of the Mid-Continent area. All of the producing sands were of Pennsylvanian age. These began to decline in 1924. However, oil was discovered in the Wilcox horizon in that year, and the total production rapidly revived. The production of the whole pool to the close of 1926 was approximately 88,000,000 barrels, of which the Wilcox sand had contributed nearly 36,000,000. All of the oil irrespective of horizon was of high quality.

---

[1] Data mainly from:

Clark, G. C., and Aurin, F. L.: The Tonkawa Field, Oklahoma, A. A. P. G. Bull., Vol. 8, pp. 269–283, 1924.

Clark, G. C.: Wilcox Sand Production, Tonkawa Field, Oklahoma, A. A. P. G. Bull., Vol. 10, pp. 885–891, 1926.

Hosterman, J. F.: The Tonkawa Oil and Gas Field, Oklahoma, A. A. P. G. Bull., Vol. 8, pp. 284–300, 1924.

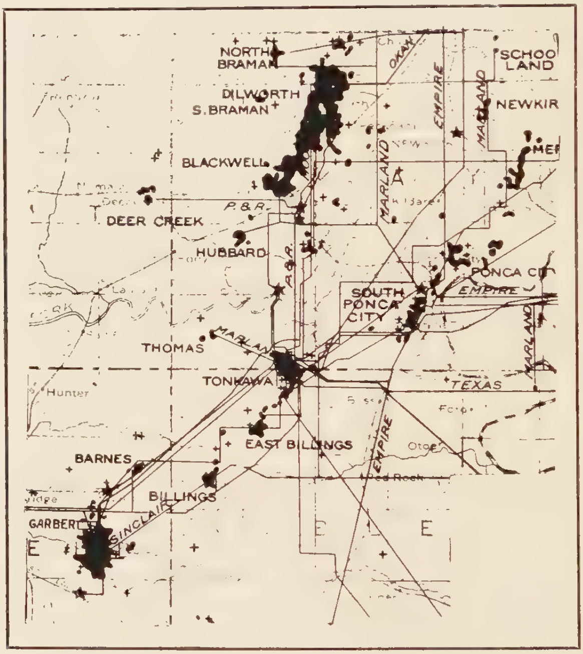


Fig. 158.—Map showing position of some of the producing pools in northern Oklahoma. After U. S. Geological Survey.

The surface beds are Permian and do not lend themselves to accurate contouring. The first marker horizon encountered in drilling is the Pawhuska limestone, which lies immediately above the

Hoover sand series. The Hoover zone is between 150 and 230 feet in thickness and contains three sands: Upper, Middle, and Lower. The Middle sand merges with the Upper in some parts of the structure and always contains water. The Upper and Lower Hoover sands contain oil, but the productive area of the Upper sand is limited to the highest parts of the major fold. The Lower Hoover production declined rapidly with decrease in the gas pressure. This zone is about 2,000 feet below the surface.

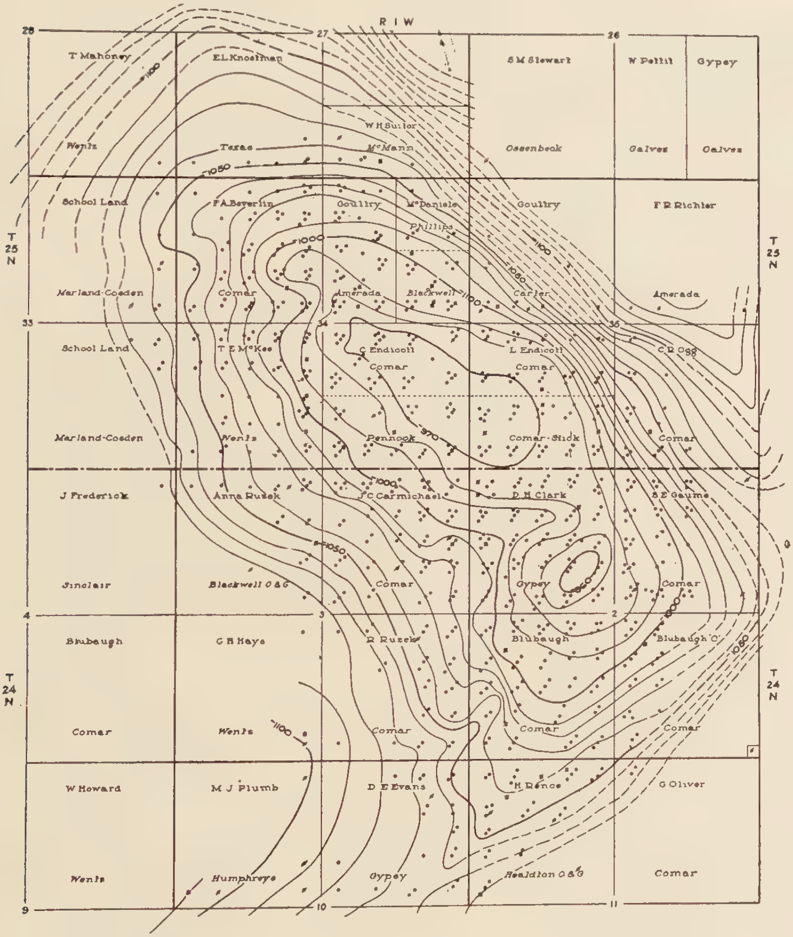


FIG. 159.—The Tonkawa pool. Contours on the Lower Hoover sand. After Clark, G. C.: A. A. P. G. Bull., Vol. 10, p. 886 insert, 1926.

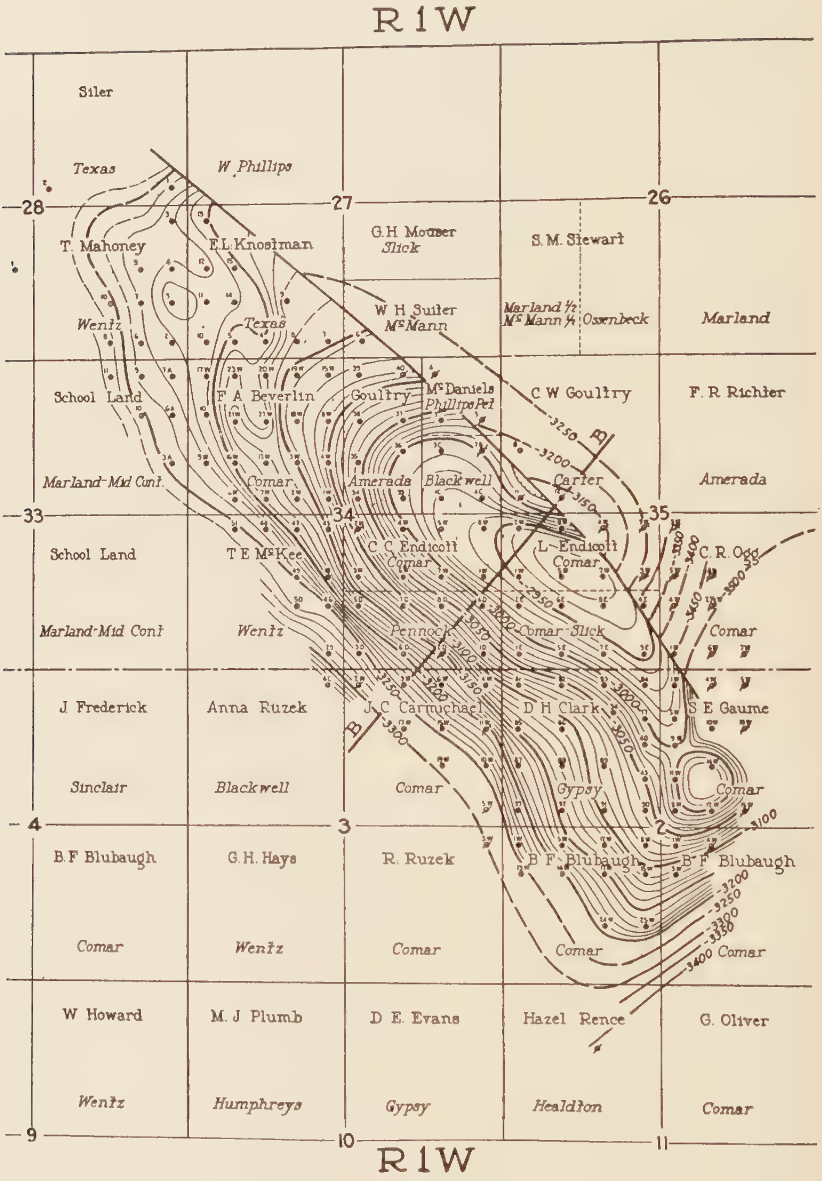


FIG. 160.—The Tonkawa pool. Contours on the top of the White Lime immediately above the Wilcox Sand. Wilcox Sand wells as developed to June 4, 1926. After Clark, G. C.: A. A. P. G. Bull., Vol. 10, p. 886 insert, 1926.

About 70 feet below the Lower Hoover is the Carmichel sand. This is a comparatively thin sand and is generally of little importance. Below this the drill showed the presence of a somewhat thicker sand called the Endicott. This has given some large wells but is more commonly a water horizon than an oil producer.

The major producing horizon during all of the early development was the Tonkowa or "2,600"-foot sand. This sand has been found to be 100 feet thick in some parts of the structure and was apparently free from major shale breaks. On the crest of the structure, the sand was found to be entirely free of water. Down the flanks a definite edge water was found below the oil. The wells were of the gusher type but also showed fairly good staying qualities.

In the lower portion of the Pennsylvanian, several sands were found, but they proved to be of little importance as oil sources. All interest in horizons below the Tonkawa has centered in the Wilcox since its discovery in 1924. This horizon was found at a depth of 4,000 to 4,400 feet depending upon the position of the well with respect to structural conditions. The Wilcox consists of two pay horizons, the upper 40 feet thick and the lower 60 to 120 feet in the thickness, separated by a barren zone of 20 to 30 feet.

The structure of the area as outlined upon the Pawhuska, Hoover, and Tonkawa sands, shows very little which might be called unusual. The structural maps of these horizons are very similar and show a very strongly developed fold having a closure of about 125 feet. The axis of the major fold shows a northwest to southeast trend but curves to the southward and slightly to the west in the southern portion of the structure. The slope to the west is relatively gentle, but that toward the east is very abrupt. There is no evidence of faulting. The Tonkawa and the sand bodies above it are regular. The thickness of the shales above the center of the structure is considerably less than that on the sides, however. The interval between the Herington limestone close to the surface and the Tonkawa sand shows a divergence of 80 feet.

The divergence between marker beds in the Pennsylvanian below the Tonkawa appears to be of the same order as in the beds above. However, the bottom of the Pennsylvanian rests unconformably upon a Pre-Pennsylvanian base. This shows distinct evidence of having been subjected to long erosion. Within the limits of the producing area alone, there is a variation of from 150 feet down to nothing in the thickness of the Mississippi lime. The underlying Chattanooga shales are entirely missing from the highest parts of the structure. A white limestone lying between the shale and the Wilcox series has resisted erosion and remains over practically all of the structure. The abruptness of the line separating the producing area of the Wilcox on the southwest from the barren area on the northeast and the marked difference in the character of the deeper portions of the wells and in the depth to the Wilcox show conclusively the presence of a major fault. The throw is to the northeast and is indicated as being about 300 feet.

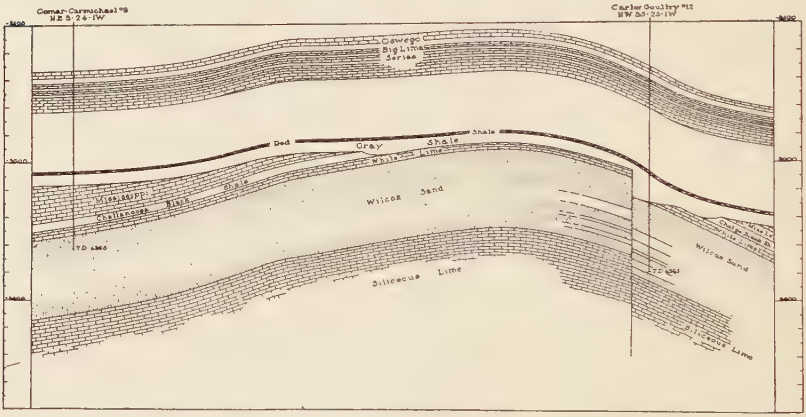


FIG. 161.—Cross-section of the Tonkawa pool along line BB of Fig. 160. Horizontal scale one half of vertical scale. After Clark, G. C.: A. A. P. G. Bull., Vol. 10, p. 889, 1926.

The fault is not reflected except by folding of much less vertical intensity in the overlying Pennsylvanian and Permian strata. Yet the fold in those beds is distinct. The only possible conclusion is that there have been two periods of dynamic action here. The first was probably at the close of the Mississippian and the second subsequent to the deposition of the Permian beds. The major faulting was evidently an outgrowth of the first period. There may have been some faulting along the same line in the later action, but this was not reflected by faults in the upper strata. The thickening of the shales may be considered as partly due to compacting or to deposition upon a base that was being subjected to some uplift. It is also possible to consider the thickening on the flanks as the result of the less competent nature of these beds.

Thomas Pool, Oklahoma.[1]—The Thomas pool in the southwestern portion of Kay County in Oklahoma is not comparable in importance with its neighbors, Tonkawa and Garber, but in the first three years of its existence yielded about 5,000,000 barrels of oil. The discovery well was drilled in May, 1924. It obtained production in a sand at 2,050 feet called the Thomas sand. This and two other sands, one at 1,900 feet and the other at 2,600, gave a small production from the Pennsylvanian. They corresponded roughly in position with the productive sands above the Tonkawa in that pool.

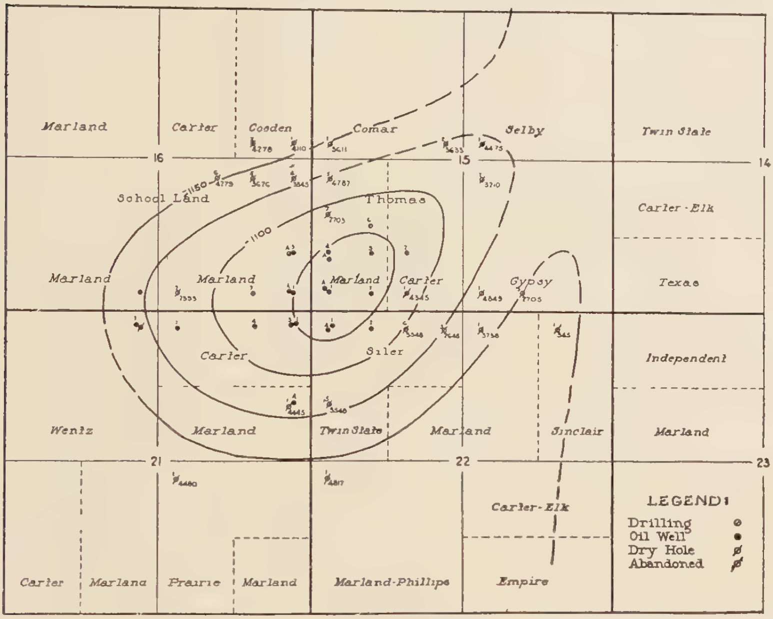


FIG. 162.—Thomas Pool, Kay County, Oklahoma. Structure Contours on the top of the Pawhuska limestone. Interval 25 feet. After Clark, S. K.: A. A. P. G. Bull., Vol. 10, p. 654, 1926.

One of these shallow wells was deepened and found the Wilcox sand at a depth of 3,955 feet. This horizon was rapidly outlined by the drill and has given the bulk of the production obtained in the pool.

The structure on the shallow Pawhuska limestone shows a slightly elongated dome. That of the Layton horizon at a depth of 3,400 feet and near the bottom of the Pennsylvanian shows much the same general outline. Dips are stronger, and the form more triangular with a longer axis to the northeast. The bottom of Pennsylvanian rests unconformably upon a Pre-Pennsylvanian surface. In the center of the structure, this is the Wilcox series. Off to the sides, the "white lime," Chattanooga shale, and Mississippi lime are exposed. Contours drawn upon the surface of the Pre-Pennsylvanian rocks show a sharply defined peak rising to the northeast. The slope of the peak to the southwest is gradual, but on the north and east sides its edge descends abruptly. The same form was shown by contours drawn upon the "white lime" and has been considered by Clark to indicate the presence of two strong faults.

---

[1] Data from Clark, Stuart K.: Thomas Oil Field, Kay County, Oklahoma, A. A. P. G. Bull., Vol. 10, pp. 643–655, 1926.

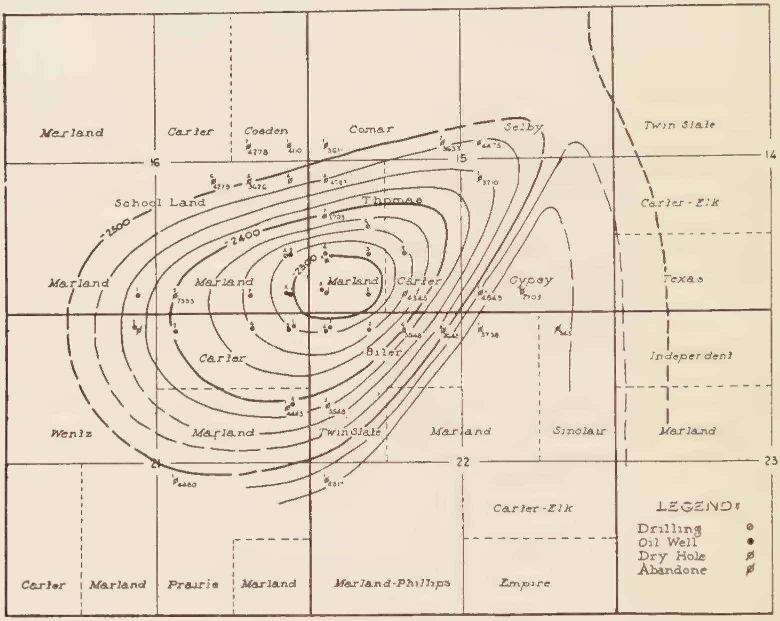


FIG. 163.—Thomas pool. Structure contours on the top of the Layton Sand. Interval 25 feet. After Clark, S. K.: A. A. P. G., Vol. 10, p. 653, 1926.

While the bulk of the oil was taken from the Wilcox, some was also obtained from chert at the top of the Mississippi lime in the western portion of the uplifted area. This is on the gently sloping portion. Some oil has been found immediately east of the eastern fault, but the amount was small, and the areas away from the uplifted block have been marked by dry holes.

The structure in these lower rocks is undoubtedly the result of dynamic movements at the close of the Mississippian. The uplift is considered by Clark to have been approximately 1,000 feet in extent. The area was modified considerably before the deposition of the Cherokee shales by intense erosion. This seems to have removed some

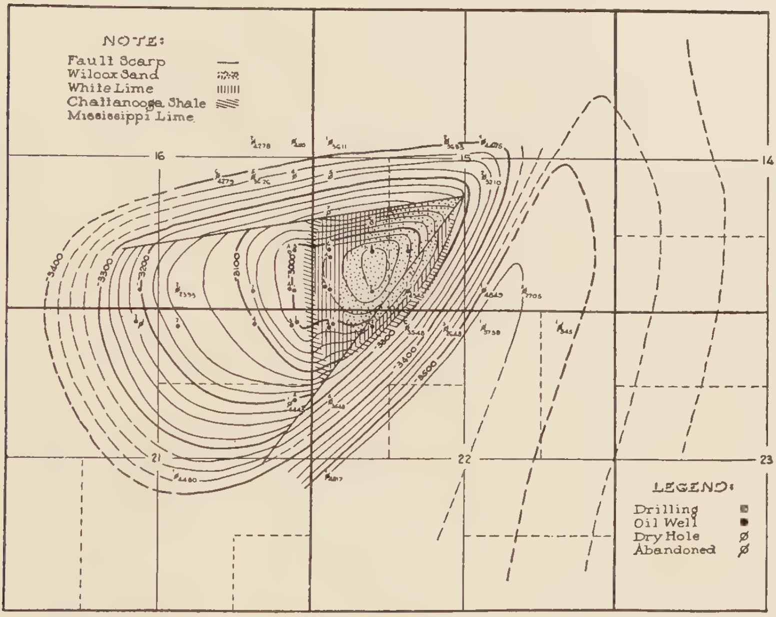


FIG. 164.—Thomas pool, Kay County, Oklahoma. Topography and areal geology of Pre-Pennsylvanian surface. Interval 25 feet. After Clark, S. H.: A. A. P. G. Bull., Vol. 10, p. 652, 1926.

400 feet of sediments from the center of the uplifted structure. Sufficient remained to impress its general outline upon the rocks above. The decrease in intensity is very rapid, the closure of the dome in the Pawhuska limestone being between 75 and 100 feet, that on the Layton 200 to 225, and of the topographic surface of the Pre-Pennsylvanian nearly 400 feet. While intermittent uplift and folding probably assisted compacting in preserving some of the outline of topographic surface, additional pronounced uplift probably occurred in the Pennsylvanian or Permian. The closure of over 200 feet in the Layton would be difficult to explain otherwise.

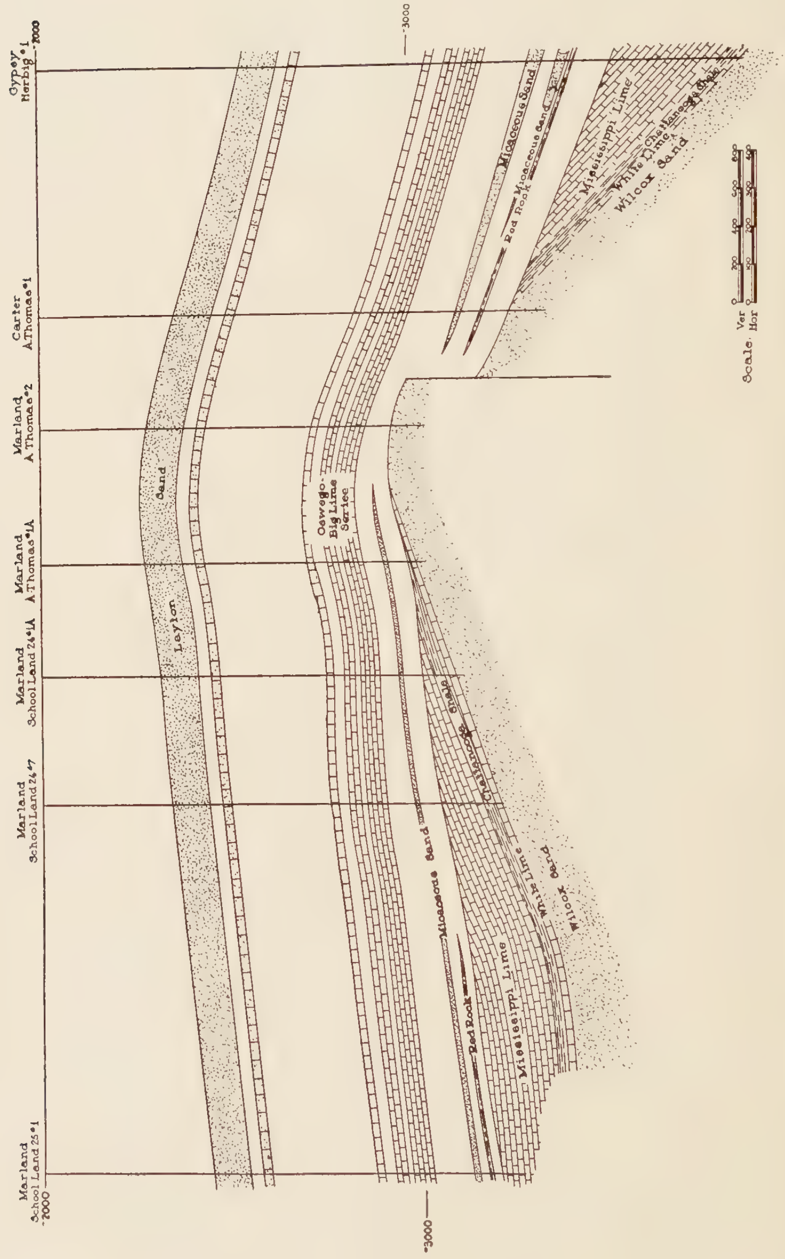


FIG. 165.—East-west cross-section of the Thomas pool. After Clark, S. K.: A. A. P. G. Bull., Vol. 10, p. 647, 1926.

Tamasopo Ridge, Mexico.[1]—Probably the most famous single producing area in the world is the Knife Edge, Tamasopo Ridge, or Golden Lane structure of Mexico. This area lies west and northwest of the town of Tuxpam in the state of Vera Cruz. The productive area extends with minor interruptions caused by doming or local faulting for a distance of more than 50 miles in a general north-south direction. Its narrowness is indicated by the names applied to it. Since its development, beginning early in the present century, it has yielded nearly 900,000,000 barrels of oil. The bulk of this has been obtained from sensational wells, from which the oil flowed under a combination of high gas and water pressures.

The expression of the structure in the upper horizons is not markedly different from that on other major folds. The slope of upper beds is comparatively steep on the western flank of the fold and gentle on its eastern side. The slope increases with depth on both sides to some extent. On the west side, it becomes abrupt when the bottom of the Eocene is reached and apparently changes into a major fault with its throw to the west.

Erosion has complicated the contacts between the Eocene and the Upper Cretaceous and between the latter and the Lower Cretaceous. The source of the oil is considered to have been shales in the Upper Cretaceous, probably the San Felipe. The main production, however, has been obtained from the highly fissured cavernous upper surface of underlying Lower Cretaceous limestones. The name "Tamasopo" is generally used in reference to the oil-containing horizon, but geologically it is probably somewhat older and should more logically be called the "El Abra." Some production has also been obtained from fractured portions of the overlying shales.

Roughly traced, the history of the area appears to have been one in which erosion, sedimentation, and dynamic action have been repeated several times. The original massive limestones, the El Abra formation, were deposited and uplifted. Some folding probably occurred. After a long period of erosion, they were submerged and the limestones and shales of the San Felipe formation laid down upon the eroded surface.

According to Powers, the deposition of the San Felipe was followed by the initiation of uplift accompanied by folding and normal downfaulting to the west. The faulting was apparently parallel to

---

[1] Mainly after Powers, Sidney: Reflected Buried Hills in the Oil Fields of Persia, Egypt, and Mexico, A. A. P. G. Bull., No. 10, pp. 422–442, 1926.

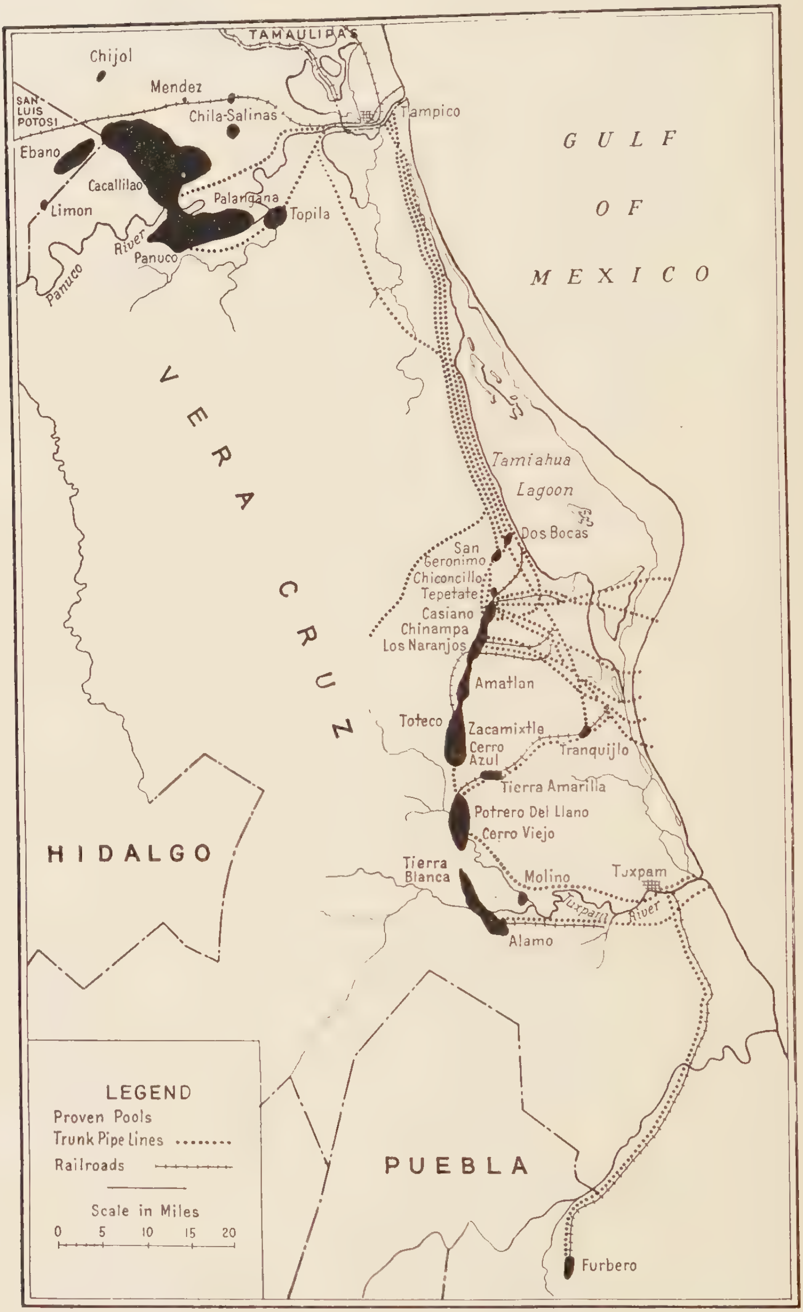


Fig. 166.—Productive areas of the Tampico-Tuxpam field. After Lilley, E. R.: The Oil Industry, p. 245, 1925.

the ridge of the anticlinal fold now productive. It seems to have been similar in many respects to the faulting at Luling and at Mexia but on a larger scale. The major uplift and faulting probably occurred at the close of the Cretaceous.

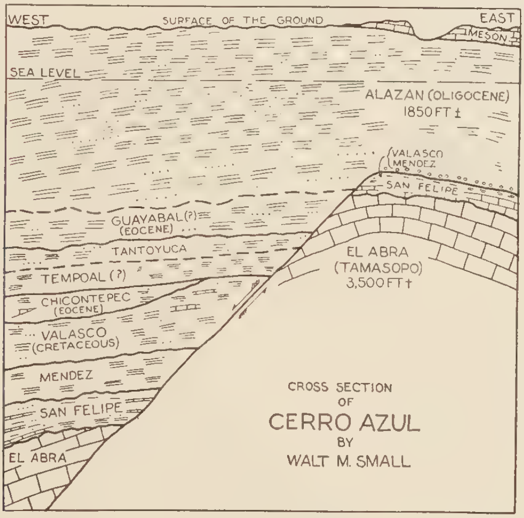


FIG. 167.—Generalized east-west cross-section of the Cerro Azul area of the Tamasopo structure. After Small, W. L.: A. A. P. G. Bull., Vol. 10, p. 441, 1926.

During the Eocene and possibly the later part of the Upper Cretaceous, the ridge area was apparently subjected to erosion most of the time. The sediments of that time are either lacking entirely or very thin and of local distribution over the arched area. The downfaulted area to the west side was consequently the only area close to the fold which received any large amount of sediments during the later portion of the Upper Cretaceous and even during the Eocene. The area appears to have been refolded in the Oligocene. This folding was of minor amount compared with the earlier but gave rise to a series of faint anticlinal arches which reflect the underlying conditions.

This description of conditions has been taken largely from Sydney Powers, whose analysis of the sediments and of the movements in the region is given in Table 62.

TABLE 62.—COMPARATIVE SECTIONS ON AND ADJACENT TO THE TAMASOPO RIDGE.*

Age	Formation	Thickness, Feet		
		West of Ridge	Above Ridge	East of Ridge (Idolo Island)
Pleistocene and Recent	Gravel, etc.	......	......	......
Miocene	Tuxpam	Absent	Absent	0–200 (?)
Major period of folding, producing structure observed in surface outcrops; intrusion of basalt; erosion	......	......	......	......
Oligocene	San Rafael, Meson	0–1,500	Absent except locally	1,000 (?)
Disconformity	Alazan	2,000	1,800–2,000	1,200 (?)
Uplift of ridge and erosion				
Eocene	Guayabal	500?	0–100(?)	
	Tantoyuca	500	Absent (?)	950
Disconformity	Temporal shale	......	Absent (?)	
	Chicontepec	2,000 (farther west)	Absent	700 (?)
Major uplift, folding and faulting; erosion of Cretaceous shale	......	......	......	......
Upper Cretaceous				
Valasco (Tamesi)	......	1,100	Occurs locally	500 (?)
Mendez (Papagallos)	......	1,500	Occurs locally	100
Initial (?) uplift of ridge by folding and faulting with downwarping of basin on the west	......	......	......	......
San Felipe	......	800–1,000	50–100 Locally absent	150
Unconformity; erosion of Tamaulipas if originally present; fracturing of ridge (?)	......	......	......	......
Lower Cretaceous (Washita) Tamaulipas limestone	......	?	Absent	0–100
El Abra limestone	......	Thickness unknown	Oil-bearing horizon; over 3,500 feet thick	(Found at 4,666 feet at Idolo Island)
Unconformity	......	......	......	......
Jurassic	......	......	......	......

* After Powers, Sidney: A. A. P. G. Bull., Vol. 10, p. 442, 1926.

Summary.—It is practically impossible to summarize the discussions of these complex producing areas. One point probably stands out more than any of the others that might be made; namely, the great length of the time elapsing between the beginning of the development of a structure and its completion. Where the arrangement of oil and gas in folded and faulted structures has been modified by sand conditions, the nature of those conditions can usually be traced to the continuance of dynamic forces similar to those which caused the development of the original structural form. Similarly, though the form of the deep producing horizon is to a large extent the product of dynamic action occurring before the upper beds were laid down, it generally shows some reflection of that action because the later forces have moved through the same general lines. Structures such as that at Big Lake, where there is practically no surface manifestation of underlying structure, are happily not common.

CHAPTER XVIII.

EXPLORATION OF NEW AREAS.

Scientific exploration in new areas is based upon conditions observed in sections in which production has been developed previously. Exploratory work is logically divided into two types. The first deals with the search for areas in which the existence of commercial quantities of petroleum appears to be probable. The second includes all of the work that might be done in the determination of areas which would be considered structurally favorable to accumulation. In the United States and in all other sections in which the drill has demonstrated the general existence of petroleum, the greater portion of the work of the geologist comes under the second heading. However, work of the first type is not entirely lacking. In less developed sections, such as, interior sections of South America, Asia, and Africa, work of the first type is of major importance and must be carried on before detailed structural studies can be logically begun.

Up to the present, the search for new areas that would be suitable for detailed study has been largely restricted to search for and examination of reported surface indications of petroleum. Such indications are found in nearly all of the world's major producing areas. They cannot always be considered as being responsible for the development of the areas in which they occur. In some cases the finding of seepage indications did not come until after the discovery wells had been drilled. In other cases, while seepages and similar indications were known, they were found at points some distance away from those in which the oil and gas were obtained in commercial amounts.

Surface indications are of various types. Some authorities would include under this general heading outcrops of kerogen or oil shales. Others include "burnt shales," beds in which the oxidation of bituminous matter has converted the shales into hardened brick-like red bodies. The author prefers to limit the use of the expression "surface indication" to those types of phenomena directly connected with oil or gas or with alteration products formed from them. Although the relationship is not fully understood, it seems advisable to consider paraffin dirt as one of the general group. The divisions which will be considered here are as follows:

1. Oil seepages.
2. Gas seepages and mud volcanoes.
3. Solid bituminous residues.
4. Paraffin dirt.

Oil Seepages.—The oil seepage may vary in size from the one which yields such insignificant quantities that it is barely able to form a thin scum over the surface of the water of a spring to one which gives a steady flow of sufficient size to be of commercial importance. Generally speaking, the active oil seepage is the most reliable of all of the types of surface manifestations of petroleum. The large active seep is easily identified. This is not always true of the small and less active types. In populated areas the contamination of spring waters by waste lubricating oils has frequently led to erroneous deductions. The casual observer is apt to confuse the iridescent film formed by iron oxide upon water surfaces with the film formed by oil. The chemical properties of the iron oxide film are naturally different from those of oil, and the difference is easily told by the geologist. The iron oxide film is easily broken up if the water is agitated; this is not true of the oil film.

Names such as Oil Spring in New York and Oil Creek in Pennsylvania indicate the early recognition of seepages in the Appalachian Field. Despite their relatively small size, such seepages were of sufficient importance to permit the gathering of oil and its sale for medicinal purposes before the drilling of the first well. Seepages in this Paleozoic area and in others of similar age were very small in size in comparison with those from the Tertiary and Cretaceous horizons in such countries as Roumania, Poland, Russia, the East Indies, Mexico, and Colombia. In many cases seepages from rocks of these ages have caused the formation of small ponds of oil. In Roumania, Alsace, Burma, Mesopotamia, Peru, and Russia, seepages have led to the digging of shallow trenches and pits into which the oil drained and from which it was collected and sold in substantial amounts.

The source of seepage oil is frequently the outcrop of the porous horizon, which at points away from that outcrop is found to contain oil and gas under substantial pressure. In other places the oil rises to the surface from a porous bed several hundred feet below through a series of more or less vertical fissures.

Active oil seepages are not necessarily restricted to land surfaces. While many of the so-called oil ponds found on the surfaces of lake and ocean waters are undoubtedly accumulations of waste oil washed out from land or given off by ships, some must be considered as coming from submarine seepages. Such occurrences have been noted in the Gulf of Mexico, the Caribbean Sea, and other water bodies adjacent to productive areas.

The large active seepage may be considered as conclusive evidence of the present existence of oil, and of the probability that it is present in commercial quantities in adjacent structurally favorable areas. The small seepage, even where it has been definitely proved to be a true natural seep, cannot be considered as proving the presence of commercial quantities of oil in the immediate vicinity. Thus, though small oil seepages have been known for many years, drilling has not yet been able to demonstrate the presence of commercially workable quantities of oil in New Brunswick, Quebec, and Newfoundland.

Gas Seepages.—Gas seepages are commonly associated with active seepages of oil. The greater mobility of gas makes its escape from within the crust much more rapid than that of oil. Thus many gas seepages are reported in areas in which oil seepages are not known. However, small seepages of gas are less readily recognized than those

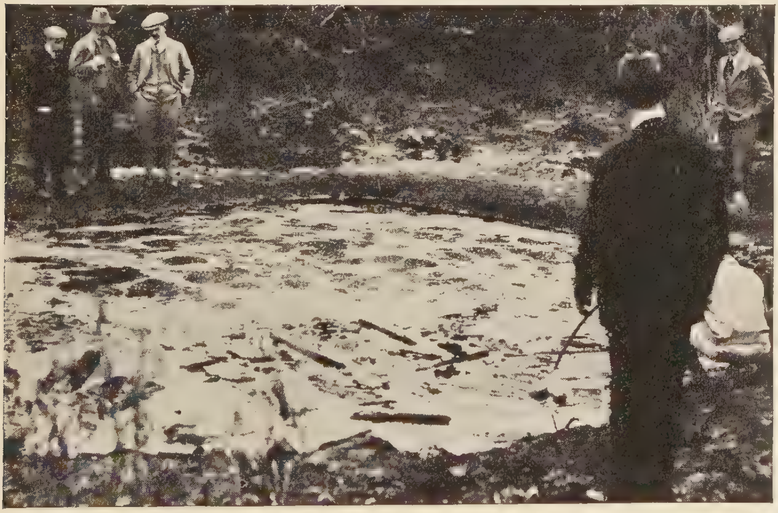


Fig. 168.—An Active Oil Seep at Tierra Blanca, Mexico. Courtesy Pan-American Petroleum and Transport Corporation.

of oil, the gas being colorless and being soon disseminated into the atmosphere. Small gas seeps are usually indicated by escaping bubbles in the waters of springs. The larger ones may manifest themselves in geyser-like explosions in which the loose dirt and water clogging the vents are thrown into the air. This type is known as the mud volcano. In others the flow is sufficiently large and continuous to support a steady flame.

Petroleum gases are sometimes confused with gases of volcanic origin. The latter differ considerably in composition in most cases. Both types contain carbon dioxide, hydrogen sulphide, and nitrogen. The percentages of the first two are, however, usually small in the petroleum gas. The bulk of most petroleum gases is composed of hydrocarbons. Volcanic gases contain substantial percentages of chlorine, carbon monoxide, boron gases, and sulphurous compounds not usually found in petroleum gases.

The most prominent of the hydrocarbon compounds found in petroleum is methane. This is also a product of decaying vegetation and is known as marsh gas. Thus identification of methane as the major constituent of a gas bubbling through the waters of a soil spring is just as likely to indicate the presence of decaying vegetable matter as it is to show the proximity of petroleum. Similarly methane is one of the prominent constituents of gases found in coal mines. As a general rule, the identification of other hydrocarbons, ethane, propane, butane, and similar volatile compounds, may be considered as proving the gas which contains them to be of petroleum origin. However, this is not always conclusive, such compounds having been identified in some marsh gases.

Gas seepages have been reported at various points throughout the Appalachian Field. In West Virginia, they have been of sufficient prominence to give the name of Burning Springs to one locality. In general gas seepages have been of minor size throughout all of the Paleozoic areas in the United States. In only a few instances can they be considered as having been responsible for the drilling of wells. Gas has been of somewhat more importance in the younger horizons. Some of the salt domes were discovered by the drilling of wells in localities in which the escape of gas had been noted. None of the seepages in the United States have been comparable with those which occur on the Apsheron peninsula and on Holy Island in the Caspian Sea. These were largely responsible for the development of the Baku district. The gas seepages have been known for many centuries and were until recently the center of fire worship, the volume of the gas issuing from the ground being sufficient to support large continuous fires.

Mud Volcanoes.—Where gas escapes through outcrops of the horizons in which it was stored, the escape is likely to occur over a wide area. While the total quantity escaping may be large, it is so spread out that there is little evidence to indicate its escape. Where gas escapes through fissures and cracks communicating with relatively deep source horizons, the flow is more concentrated and therefore more evident. In some instances the flow is not continuous but takes the form of a series of intermittent explosions. Such types of gas seepages are known as mud volcanoes because of the quantities of mud and water that are thrown up at each eruption.

A large percentage of the material thrown up falls back into the vent and assists in retarding the escape of more gas and thus in the building up of pressure for the next eruption. Part of the material is thrown to the sides and forms typical cones. Cones may vary in size from a few inches up to 100 feet in height. The best method of identification of the source of the gas in such areas is the analysis of the gas that is given off. Where the mud volcano is no longer active, examination of the material which forms the cone is usually sufficient to distinguish such cones from those formed by fumaroles, geysers, or ordinary volcanic action.

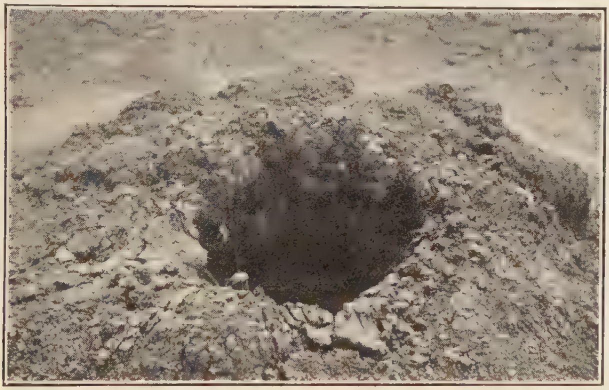


FIG. 169.—Cone and crater of an active mud volcano, Trinidad. Courtesy Standard Oil Company of New Jersey.

Mud volcanoes of relatively small size have been found in Colombia and Trinidad. Others are known in the East Indies and in Roumania. The largest and best examples of this type of indication are found in the Baku district of Russia and in parts of Burma.

Gas seepages may usually be considered as reliable indications of the presence of petroleum and natural gas. However, the possibilities of the gases being formed through agencies wholly unrelated to those which form petroleum make it necessary to give the closest attention to their character and to phenomna with which they are associated before drawing definite conclusions.

Solid Petroleum Residues.—Under the heading of solid residues of petroleum would be included the various types of asphalts, the vein asphalts or asphaltites, asphaltic or bituminous rocks, natural waxes, and pyrobitumens. The close relationship in origin between these substances and petroleum offers good reason for expectation that they should be reliable indications of the presence of petroleum. Yet it must be recognized that they are produced by the alteration of petroleum and are more strictly indications of its former existence than of its presence.

Surface deposits of relatively pure asphalt are prominent in the oil fields of California, Mexico, Peru, Trinidad, Russia, the East Indies, and other areas producing from Tertiary and Cretaceous horizons. Some of the asphalt deposits are of great extent, the Pitch Lake of Trinidad being about 137 acres in area. Its depth at the center is not known.

Asphalts are not always indicators of the presence of commercially recoverable amounts of petroleum. Thus in Cuba, the drill has failed to demonstrate the existence of more than the most minor amounts of petroleum in the vicinity of the asphalt deposits. The value of an asphalt deposit rests largely in the age of its formation. Each one must be considered as the product of the alteration of the oil, which has come to the surface in an active seepage, to a solid by surface agencies. If of recent formation, the chances are good that unaltered oil still remains in sections adjacent the deposit. If of old age, there is greater probability of all of the oil having been converted into solid matter by reactions with artesian waters, or having escaped to the surface.

In some areas, such as California, tar- or asphalt-saturated sands are of common occurrence in the vicinity of producing wells. The bituminous matter contained in the pore spaces of some rocks must be considered as liquid matter, which is held there by the adsorptive powers of the rock matter. In the true bituminous beds it is solid matter, resulting from reactions between oils and circulating waters or remaining after the escape of the less viscous portions of the oil. The tar sands of California are duplicated in the producing areas of Russia and Venezuela. On the other hand, no oil has been obtained from wells drilled in the immediate vicinity of the Athabasca tar sands in northern Alberta. Yet these are the most extensive group of such beds that are known at the present time. Similarly, while deposits of bituminous limestone are known in Germany and France, the yields of oil from wells drilled in the same areas have been of little importance.

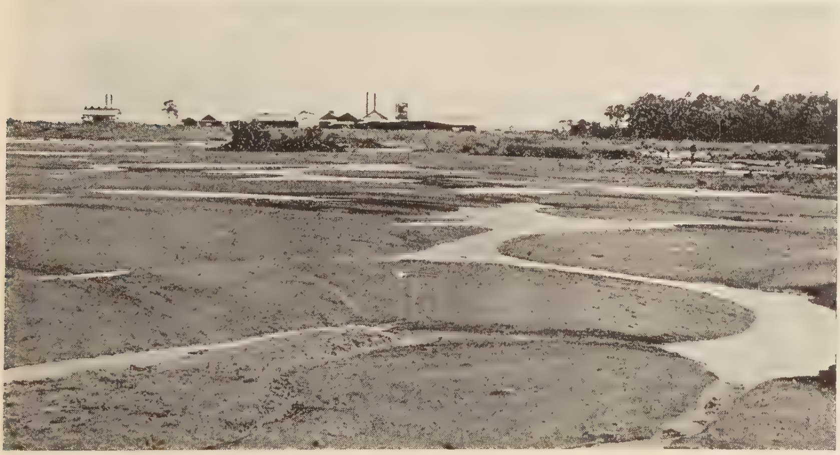


Fig. 170.—A portion of the Trinidad asphalt lake. Courtesy Barber Asphalt Paving Company.

Veins or dikes filled with solid bitumens are found in some oil fields. Thus a dike of grahamite of large size is found in Ritchie County, West Virginia, near the Burning Springs-Volcano anticline, one of the largest producing structures in the Appalachian field. Ozokerite is found in strata near and above those which contain oil in Galicia. The relationship, however, is not always clear. Grahamite has been found in south-central Oklahoma, but the section in which it is obtained is not one which is productive of oil. Wurtzilite deposits are known in Utah but have not indicated the presence of oil up to the present. Similarly, the famous albertite veins of New

Brunswick have not been an indication of the presence of commercially recoverable amounts of petroleum.

It does not appear that pyrobitumens can be given much value as indicators of the present existence of oil in any region. Vein asphalts, ozokerites, and bituminous rocks may be considered as favorable indications, but their presence is far from conclusive evidence. Somewhat greater faith can be placed in the surface asphalt deposit, especially if it is of recent formation. Such deposits are commonly associated with active gas and oil seepages, which must be considered as more reliable indications.

Paraffin Dirt.—Paraffin dirt is a substance concerning whose nature there is considerable debate. Some investigators have considered it to be a substance wholly unrelated to petroleum and natural gas and therefore of no importance to the prospector. Though little is definitely known about its origin and character, the number of instances in which it has been found above points on the Gulf Coast plain from which oil and gas were later obtained tends to indicate some definite relationship and value to the prospector.

Paraffin dirt has been defined by D. C. Barton [1] as an argillaceous soil permeated by a definite chemical substance that is organic in origin, formed by bacteria living in part at least on methane and oxygen. Paraffin dirts are characterized by rubbery textures but, while elastic, lack the cohesion of rubber. The name "paraffin dirt" is a misnomer as the substance contains no paraffinaceous material. It appears to be masses of organisms of very low rank in a gelatinous matrix. The substance is most prominent within three inches of the surface, decreasing rapidly in amount below that depth.

Though there is great difference in opinion between Gulf Coast observers concerning the manner of its formation, there seems to be fairly general agreement that paraffin dirt can only be formed where there is constant, localized ebullition of methane gas. While the possibility that sufficient quantities of methane may be generated by the decay of surface matter is admitted, and the use of paraffin dirt as an indicator of the existence of petroleum and natural gas in other areas is open to criticism, the close relationship between its occurrence and the presence of oil and gas in the Gulf Coast area have led geologists to consider it a reliable indicator in that section. To oil operators there it is as important as an actually observed gas seepage.

---

[1] A. A. P. G. Bull., Vol. 9, p. 1120, 1925.

Sections Having No Surface Indications.—Many of the surface indications discussed would be passed by without further thought by all but the most careful observers. Many of the less striking indications are entirely forgotten until after the drill has demonstrated the presence of oil. Surface indications are insignificant in importance in the Paleozoic fields of Kansas, Oklahoma, and Texas. The same may be said of their relation to the development of production in Illinois, Indiana, and Ohio. The discovery well at Comodoro Rivadavia in southern Argentina was drilled to provide water for a governmental station.

Many of the discoveries in other areas have been due purely to chance. The proportion of those which are the result of careful geologic study may be expected to increase in the future. Investigations in areas having no known surface indications must naturally be based upon careful examination of other types of evidence. The nature of some of this evidence was discussed in a general way in Chapter V. Certainly there is no reason to condemn an area of sedimentary rocks merely because it is lacking in surface indications. In some instances, the presence of so-called surface indications, the tar sand, the dried-out asphalt, the bituminous limestone, or the pyrobitumen vein, is a better indication of the escape or alteration of the petroleum than of its presence. In sections having no reliable surface indications, great importance must be attached to the presence of beds whose composition and appearance indicate their possible function as source beds. The degree of alteration of the sediments becomes a factor of importance, as metamorphic agencies tend to destroy oil deposits at the same time as they metamorphose rocks.

Regional Structure.—Even the active oil seepage, generally considered to be the best indication of petroleum we have, proves little more than the presence of oil in immediate proximity to the point where the seepage occurs. If the seepage is of the fissure type, it does not even indicate the stratigraphic position of the horizon from which the oil was originally derived. In this respect the outcrop seepage is of considerably greater value. The majority of fissure seepages appear to be limited to sections in which the source horizons lie within reasonable distance of the surface. Outcrop seepages are practically always found at the crests of anticlinal areas, in uplifted faulted sections, or on the rims of synclinal basins. Seepages, both of the fissure and the outcrop type, are very seldom found in sections of synclinal form.

In the intensely folded and steeply dipping beds of the Tertiary and Cretaceous in which surface indications are most pronounced, the horizons that are indicated as potential producers may be covered by great depths of later sediments in sections close to the point of outcrop. In such areas ability to estimate the depth at which the horizon should be found in structurally favorable sections becomes of extreme importance. Similarly the close relationship between productive sands and limes and dark colored shales indicates the desirability of penetrating certain recognized source beds before abandoning tests.

The determination of the extent and of the depth of possible productive horizons or of potential source beds is based upon studies of regional structure rather than of local structure. It is in this type of work that the publications of governmental organizations, such as the United States Geological Survey and the various state surveys, and of associations of geologists become of major importance. The data contained in them may have no direct bearing upon the subject of petroleum but may give much usable information about the position of the beds which control its presence.

Early development work in new provinces is almost always limited to the rim areas of regional or geosynclines and to the most prominent of the regional uplifts contained in the larger basins. In Wyoming today production is almost entirely limited to structures on the rims of the basinal areas. That of northern Montana is found entirely upon the uplifted Sweetgrass Arch. The production of Baku, Grosny, and Maikop in Russia, lies on the uplifted rims of the major synclinal sections. The early development work in the Los Angeles Basin of California was limited to the shallower eastern and northern portions. The operators in the North Mid-Continent and the Appalachian areas have worked steadily from the eastern and northeastern sections of shallow production to the western and southwestern areas where the horizons are deeper.

In part this tendency can be traced to the close proximity of seepages to the rim areas. In part it is due to greater knowledge of the positions of the potentially productive horizons. In no small measure it may be traced to the lower cost of drilling shallow wells. The absence of strong local structures has been noted as an unfavorable indication in many synclinal areas. Yet the geologist is steadily extending producing areas toward these basinal sections. In some the absence of local structures has proved to be more apparent than real, the structure of the deeper beds being concealed by later sediments.

In the development of such areas, the geologist must rely more and more upon his understanding of basic conditions, and less and less upon surface manifestations. In such sections, further difficulties are added by the necessity of depending upon data obtained from the drilling of wells. In this work, microscopic examination of drill cuttings and cores by the petrographer and the paleontologist becomes of first importance.

Local Structural Conditions.—Just as the early work of the prospector was limited largely to areas in which surface indications of petroleum were most prominent, so the geologist restricted his recommendations to those areas in which favorable local structural conditions were most evident. Except in a few areas in which the dominating importance of faults was recognized, such recommendations were largely restricted to anticlinal areas. This meant almost invariably the anticline that could be located by examination of outcropping strata. With the completion of test wells upon such structures, the number remaining to be found in the more developed areas such as the United States is steadily decreasing. The demand for oil, on the other hand, is steadily rising and is forcing the geologist to utilize other types of information than that supplied by outcrops in making his recommendations. This does not mean that the surface survey using the barometer, the handlevel, the Brunton compass, or the plane table and alidade, is no longer used but rather, that additional tools are being added to make the recommendations more certain.

Such tools may be considered as of two types: those which are used primarily in adding directly to information gathered from surface observations prior to the drilling of any wells, and those which are utilized to extend production after the completion of tests. Under the first heading, work done with the diamond drill and investigations by geophysical methods stand out as of major importance.

Diamond Drilling for Structure.[1]—In many sections the presence of structures suitable for accumulation of oil and gas is indicated in a general way by the attitude of the outcropping rocks, but the small number and the poor quality of the outcrops present make definite outlining of the structures impossible. The making of definite recom-

---

[1] For technic of diamond drilling see Edson, Frank A.: Diamond drilling, U. S. B. of M. Bull. 243, 1926.

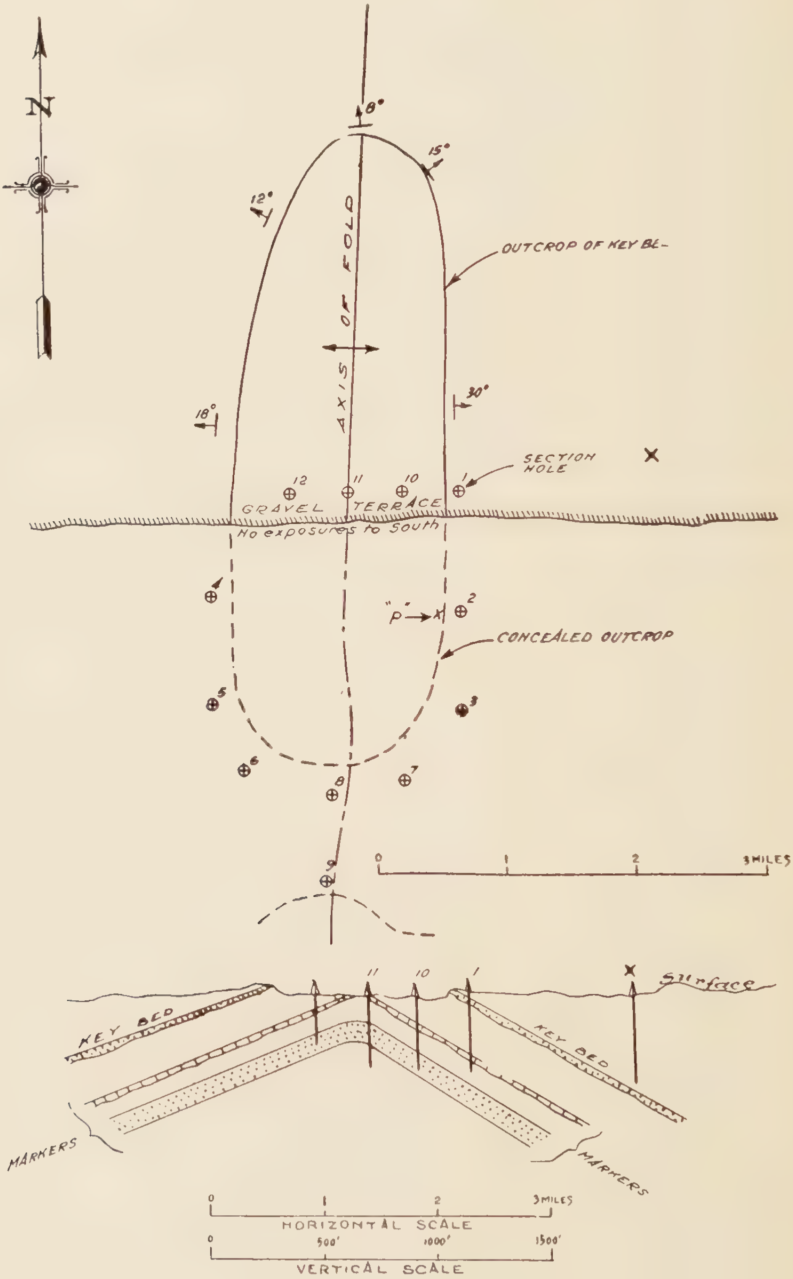


FIG. 171.—Plan showing diamond drill tests upon an unfaulted anticline and cross-section drawn from diamond drill data. After Bartram, J. G., and Wilson, J. H.: Petroleum Development and Technology in 1925, p. 55.

mendations for test locations without further information is extremely hazardous. The difficulties arise from two types of conditions. First, prominent outcropping horizons found in sections near the structurally favorable areas may be covered by soil, glacial débris, river deposits, and similar material of recent age. In some instances the covering may consist of relatively old lithified beds which rest unconformably upon the top of those whose structure it is desired to determine. The second difficulty is that resulting from the inability to determine corresponding points in different outcrops of the same bed because of the effects of weathering.

The logical way to determine the elevation of desired parts of a bed whose weathered outcrops yield data of uncertain quality is by examination of its unweathered portions. The digging of trenches back from outcrops to reach unweathered portions has been common practice for many years. In some places shallow holes or pits were dug until the desired bed was reached. The pick and the shovel were tools that were usually available, and the method was cheap and effective provided the bed was close to the surface. When the overburden reached a thickness of more than 30 or 40 feet, such work became difficult, slow, and costly. In a few sections churn drills were utilized to carry test holes to greater depths. They were fairly successful in sections in which the key beds were easily recognized.

In most sections the key beds do not differ greatly from those above and below them. As the churn drill ordinarily yields only cuttings, it is not always possible to identify the different beds with perfect security. The logical tool was soon found to be one that would yield cores which could be examined by the geologist, stored away for further reference if necessary, and compared with other cores as might prove desirable. Such cores could be obtained from either the diamond drill or the steel shot drill. Very little work has been done with the latter, but the diamond drill was soon proved to be an exploratory tool of major importance and is now considered to be an essential part of the equipment of the large producing oil company.

In many places the outcropping beds that serve to indicate the broadly favorable structure have been eroded from the important central areas. In such cases it may be necessary to drill to considerable depths to reach a non-outcropping horizon, which can be used as a key bed to determine the best location for a test well. Such key beds may not be encountered unless holes of 500 to 600 feet are drilled.

Even greater depths may be necessary where it is desired to outline the structure of beds lying below a marked unconformity. As a number of holes are needed to outline even the simplest type of structure, the cost is large. In faulted areas, the close spacing of holes sometimes makes the number of holes so large that there is doubt as to the desirability of continuing the work of exploration. The results in most cases, however, are more than sufficient to warrant the expenditure.

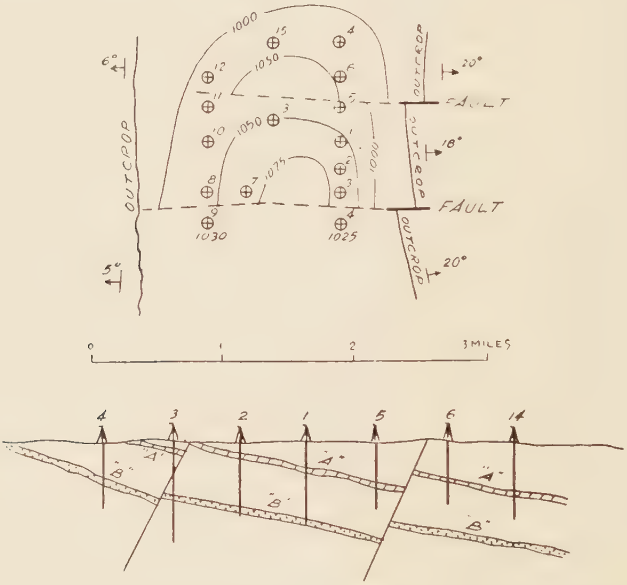


FIG. 172.—Plan showing location of diamond drill tests upon a faulted anticline and cross-section based upon data secured from them. Cross-section not to scale. After Bartram, J. G., and Wilson: Pet. Dev. and Tech. in 1925, pp. 56 and 57.

Results have been of two types. In some cases the diamond drill has supplied sufficient information to prove the non-existence of supposed favorable structures and thus prevent the expenditure of large amounts of money in the drilling of wells that were doomed to fail. In others it has served to outline structures sufficiently to permit the selection of test hole sites in which the maximum chance of success was present. The diamond drill has been used to some extent in the Rockies, in Texas, and in other areas; but its greatest successes have been scored in Oklahoma and Kansas. The largest of the pools in whose development the diamond drill was of major importance was Tonkawa. Others in these two states include such pools as Thomas, Hubbard, North Braman, South Braman, Deep Rock, Hunnewell, and Graham.

Geophysical Prospecting.—Up to the present the diamond drill has been used as a tool to supplement surface work. No attempts within the knowledge of the author have been made to use it as an exploratory tool in sections in which no indications of favorable conditions were shown by outcropping beds. While geophysical methods have been used in part to test locations in which surface indications or outcropping beds indicated favorable conditions, they have also been used with success in sections where such indications were unknown. Although only recently applied to prospecting for petroleum, geophysical instruments have met with such success in the salt dome areas of Texas and Louisiana as to warrant giving them most careful consideration. The highly technical nature of the principles upon which they are based and the limited amount of reliable information about their operations available outside of the files of those companies and individuals which have been instrumental in their development, make it impossible to give concise summaries of their nature and action. Because of this, discussion here must be limited to very brief and general statements about their nature and to short summaries of their accomplishments.

Geophysical methods are commonly divided into five groups. These are as follows:

1. Gravimetric methods, including especially use of the torsion balance.
2. Seismic methods.
3. Magnetic methods.
4. Electric methods.
5. Radio wave utilization.

The study of the use of radio waves is still in its initial stages. Investigations are being made to determine differences in the reactions of petroleum, salt water, and the several types of strata present in oil fields, to radio transmission. While methods based upon such differences may be developed sufficiently to warrant their application to the location of oil in a commercial way, much still remains to be done before this stage will be reached.

Methods utilizing differences in the electric conductivity of different substances have been used with considerable success in prospecting for metallic ores. Salt water is a good conductor of electricity while petroleum is a non-conductor. However, up to the present no method utilizing this difference in electric conductivity or differences in the conductivity of various strata has given sufficiently consistent results to warrant being considered as commercially usable.

Methods utilizing differences in the magnetic qualities of different types of rocks have been used to some extent. They appear to be best fitted to operations in locations where buried igneous masses, such as those of the Panhandle area of Texas, are present. It should be noted that this method is strictly an indirect one; that is, it is based upon the idea of finding structural conditions in which the accumulation of oil and gas may be expected rather than the finding of the oil itself. In sections where accumulation occurs at the base of sediments which have been deposited over irregular crystalline masses or in continuous beds which have been arched by uplifts along the line of crystalline ridges, this method holds considerable promise because of the presence of magnetic minerals in such masses. Cores of crystalline rocks having sufficient magnetic properties to make determination possible have been found in only a limited number of productive structures. It does not appear that such material will be found underlying more than a relatively small proportion of the world's structures at points sufficiently close to the surface to make their determination possible. There is much room for improvement in the instruments in use today.

The best results from geophysical surveys in oil fields have been obtained through the use of seismic and gravimetric methods. They are used together to a large extent today, the seismograph being used for reconnaissance work and detail work, while the gravimetric method is reserved solely for detailed work. This is due largely to the slowness of the latter method rather than to any superior results obtained through the use of the seismic method.

The gravimetric methods are based upon differences in the density of different types of materials that compose the crust of the earth. Such differences are most marked where ridge-like or dome-like masses composed of one type of material are surrounded by material of entirely different composition. Such conditions are present where massive crystalline rocks of irregular outline are surrounded by partly compacted sediments. The differences between the densities of salt dome cores and the surrounding sediments are less marked but are still sufficient to be indicated by the highly sensitive torsion balance if the top of the dome comes within reasonable distance of the surface.

Today the seismograph is being used more than the torsion balance, though the first successful work was done with the latter instrument. The torsion balance is being used more in checking up the areas that are indicated to be favorable by the seismograph than as a primary instrument of search. The seismograph used by oil companies is based upon the same general principles as the seismographs used for many years to record earthquake action. Instead of recording natural earthquakes, it records the transmission of the vibrations caused by setting off high explosives. As the crystalline salt domes react very differently from the sediments surrounding them to such vibrations, detection of their presence becomes possible. Similar results may be obtained in the future from other combinations of rocks, but comparatively little is known about them today. In the Gulf Coast territory the seismograph is now considered as being capable of obtaining results to depths of 8,000 feet and over distances of 10 miles.

The reputations of both the seismograph and the torsion balance as tools for exploration for oil rest solely at the present time upon their success in the Gulf Coast territory of Texas and Louisiana. The first torsion balance was placed in this field in 1922 and the first seismograph in 1924. The presence of the first salt dome indicated by the torsion balance was proved in July of 1924 when a test well at Nash drilled into cap rock at 639 feet. This dome was later proved to have caused the accumulation of commercial quantities of oil, the production in 1926 being 207,000 barrels. The discovery of commercial quantities of oil was not made until January of 1926. Domes were discovered and proved at Orchard and Long Point in the latter part of 1924. The presence of the first of these was indicated by the seismograph; the second, by the use of the two instruments together. During 1925, domes were located at Fannette, Hawkinsville, Stark, Allen, and Clemmons. In 1926, the Moss Bluff, Feusse Pointe, and Napoleanville salt domes were located and the presence of dome material proved by the drill. By the close of 1927 the number of salt domes found by these methods had reached thirty.

In all of these tests the dome material was found at depths of less than 1,500 feet. Considerable uncertainty remains, even with the marked improvements that have been made in the character of the instruments and in the interpretation of the data in the last two years, as to the ability of the instruments to locate domes that are much more deeply buried. The cost of geophysical methods of investigation is not low. It has been estimated that the oil industry had spent more than a millon dollars for each of the domes that had been found up to the end of 1926.

Much of the territory of the Gulf Coast plain has been gone over by geophysical testing parties, particularly by those using the seismograph, as that type of instrument is now capable of covering as much as 250,000 acres in reconnaissance in a month. The detailed work necessary whenever promising indications are noted is naturally much slower. It is still too soon to make predictions about the future of such methods of exploration.

Not all of the salt domes which have been known for many years have been found to be productive of oil. It can hardly be expected that all of the domes discovered by geophysical methods will be productive. The determination of the absence or presence of oil after the finding of the dome is extremely expensive. Production may be obtained from above the cap, within the cap, or off to the flanks of the salt core. One flank may be found to be productive and all others to be barren. The first producing well on the Nash dome was 4,127 feet in depth and that on the Orchard dome 3,750 feet.

The number of possible discoveries in the Gulf Coast area naturally decreases each year. While areas having somewhat similar salt cores are prominent in Roumania, Germany, and in southern Mexico, they are not of common occurrence in most fields. The seismic, gravimetric and other methods utilizing geophysical principles may prove to be just as successful in sections in which other types of structures are common, but at present their commercial value in such areas is practically unknown.

A SELECTED BIBLIOGRAPHY ON METHODS OF GEOPHYSICAL EXPLORATION.

1. Ambronn, Richard, Methoden der Angewandten Geophysik, 1926.
2. Barton, D. C., The Eötvös Torsion Balance Method of Mapping Geologic Structure, A. I. M. M. E. Tech. Pub. No. 50, Feb., 1928.
3. Gutenberg, B., Lehrbuch der Geophysik, Abschnitt XXII, Geophysikalische Aufschlussmethoden, 1926.
4. Heiland, C. A., Instruments and Methods for the Discovery of Useful Mineral Deposits, Eng. and Min. Jour. Press, Vol. 121, pp. 47–58, 1926.
5. Pautsch, Erich, Methods of Applied Geophysics for Exploration of Oil, Ores, and Other Useful Deposits, 1927.

Subsurface Tools.[1]—The feasibility of geophysical methods still remains to be proved in the great majority of the world's producing fields. Yet in these, just as in the salt dome and crystalline rock core areas, the absence of outcropping strata and the lack of conformity between shallow and deep producing horizons retard the discovery of new pools. The value of the shallow diamond drill hole is recognized where no unconformities are present immediately above the productive horizon. In sections where buried structures have little or no surface manifestation, the diamond drill has only limited application. It is of little value in the development of sections like Burbank where the controlling factor is the changing porosity of the deeply buried productive horizon. In such areas the only data that can be used to any great degree is that which becomes available by the drilling of wells. Some of these may be drilled in adjacent areas in which surface indications of structure have led to drilling. A large number of the wells that were drilled in such areas and have contributed to the information about subsurface conditions were located without regard to structure and purely upon a "hit or miss" basis.

Until recently the records of such wells were made with very little regard for their utilization in later operations. The profits of the contractor, who agreed to drill a given hole to a definite depth for a certain lump sum or price per foot, depended entirely upon the speed with which he completed his work. As careful sampling and logging of the hole tended to slow up the work, he frequently paid the minimum of attention to it. The closer control now being exercised by the geologist over the taking and keeping of samples and records, together with the fact that an increasing number of producing companies are operating their own drilling tools, is tending materially to improve the quality of drilling records and to develop systematic sampling. Many concerns make a policy of having geologically trained men on hand to take the samples on the more important tests.

---

[1] Most of the more recent volumes on petroleum engineering such as "Petroleum Production Engineering," by L. C. Uren, and "Petroleum Production Methods," by J. R. Suman, contain discussions on sampling and coring technic. The technic of identification of the minerals in sedimentary rocks has been discussed at some length by H. B. Milner in "An Introduction to Sedimentary Petrology" and "Supplement to an Introduction to Sedimentary Petrology." The Journal of Paleontology, first issued in 1927, is now a medium of exchange for ideas on the identification and correlation of oilfield formations by paleontological and micropaleontological evidence.

Not all of the inaccuracies apparent in drilling records can be blamed to carelessness. The nature of the rotary unit makes close identification of the material passed through practically impossible in many instances. The proved failure of the rotary to note the presence of substantial amounts of oil and gas in important tests made it a wildcatting tool of questionable value. Even the cable tool driller was frequently confused by the mixing of cavings with the material through which he was drilling.

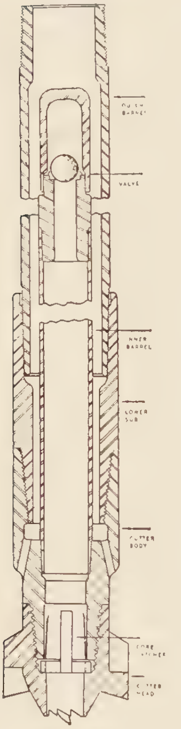


FIG. 173.—A typical rotary core barrel, the Elliott Alco model.

Naturally the deductions of the subsurface geologist could be given no higher rating than that of the data upon which they were based. Recognition of hard limestones and thick bodies of sand in otherwise shaly sections was to be expected. Their correlation where wells were closely spaced was not difficult. However, deductions concerning the relative ages and stratigraphic positions of beds in wells some distance apart were most unreliable. Thus erroneous correlation of the deep producing horizon of the Cushing pool with the Glenn or Bartlesville sand of the Glenn pool retarded the development of the area between and south of them for at least five years. It caused many wells to be abandoned as dry, when they penetrated the true Bartlesville and Dutcher sands, which would have been large producers had they been continued to the underlying Wilcox, from which the bulk of the so-called "Bartlesville" at Cushing was actually obtained. Correlations based entirely upon comparisons of drillers' logs must be considered as of doubtful value. Somewhat greater accuracy can be credited to correlations in which the geologist has been able to examine the cuttings of the wells under the microscope. The most accurate results demand that the core be available for detailed examination under the microscope by the competent petrographer and the micropaleontologist.

It is generally admitted that the diamond drill takes the best type of core. However, the cost of drilling to the depths now common in the majority of the world's important fields with the diamond drill makes its use impractical in most instances. The technic of taking cores with the rotary outfit has developed rapidly within the last few years. Relatively few cores have been taken with cable tools, but the practice is increasing. The policy of taking cores has made it possible for the micropaleontologist to make much more definite correlations between wells and between formations penetrated by the drill and those seen at distant outcrops.

Limitation of Geologic Activity.—The activities of our larger producing companies are spread over the United States, and in a number of cases into several foreign countries as well. At the same time activities within each major area are largely restricted to work in relatively small subdivisions. The choice of such areas is determined either by general knowledge of the geology of the areas or by close study of the developments already made. Thus, though much of the rest of Venezuela must be ranked as potential territory, operations are largely restricted to the Maracaibo Basin at the present time. Similarly development work in Colombia centers in the narrow synclinal valley of the Magdalena River and the coastal plain on the shore of the Caribbean Sea. Such restrictions are based upon knowledge of regional structure.

In the more highly developed fields of the United States the restriction of activities is even more marked. Geologic work is almost entirely limited to the rim areas of the Powder River and Big Horn Basins of Wyoming. In the latter, distinctions are made between the desirability of testing the structures lying close to the mountains surrounding the basin and those lying nearer to the axis of the basin. In these and similar areas in the Rockies the structures are largely visible in the surface beds. In the Paleozoic areas of the Mid-Continent Province, the recently developed pools in the Tertiary of the Los Angeles Basin, and the Cretaceous of Texas, Louisiana, and Arkansas, the absence of good surface indications forces the geologist to base his work upon the less easily procurable subsurface data. In such areas successful work is largely the result of the accumulation and interpretation of the data supplied by hundreds of test wells. Intimate knowledge of individual areas demands that the geologist devote his entire attention to relatively small sections.

The results of such detailed studies are apparent in maps showing drilling activity; their causes are not always evident to the casual observer. The dominating influence of the Mexia fault line and its continuations is indicated by the absence of drilling wells in sections away from its supposed trace. With the realization of the extent of the Inglewood uplift in the Los Angeles Basin, practically all other wildcatting was abandoned so that the companies could be able to devote their full attention to operations along the line of this major fold or fault. In Oklahoma the line of proved pools extending from Mervine to Garber and including such important areas as Billings, Ponca, and Tonkawa, gives ample indication of the continuity and importance of the deeply buried ridges which have caused their presence. The discovery of Tonkawa may be considered as due largely to the realization of the existence of an uplifted ridge and the restriction of geologic work to sections between previously developed structures on that ridge.

The restriction of operations is not always based upon purely structural data. The heterogeneous arrangement of the structures in the eastern part of Osage County, Oklahoma, makes the development of any working theory of the arrangement of the structures difficult. Production is nevertheless limited to definite zones. These were found to depend upon the existence of porous areas in the lime and sand horizons from which production was obtained. In this area and sections adjacent to it, work was largely restricted to those portions in which the examination of drilling records and samples indicated the former existence of conditions suited to the deposition of porous sands or the development of porosity in limes.

A most striking limitation of drilling activity occurs in the shoe string sand areas of Kansas, where practically all of the efforts of the wildcatter and the geologist are limited to attempts to extend the string-like producing belts and to fill in the gaps between already discovered portions of a single string. In much the same manner, drilling activity in search of gas in the Clinton sand in Ohio is definitely limited on the west by a line running north and south, that is believed to mark the pinching out of that horizon.

Non-producing Structures.—All prospecting for petroleum involves a certain degree of uncertainty because of its indirect character. The well developed structure located in an area in which suitable source and reservoir beds are known and the degree of metamorphism is not too great is the logical place to test. However, tests in which every known factor favors success have failed to obtain production. The location of the salt dome is considered as the first step in the exploration for new pools in the Gulf Coast area of the United States. Yet it is recognized that many of the known domes have failed to yield commercial quantities of oil. It is probable that some of the domes which are non-productive at the present time will yield oil in the future. The number of tests that have been drilled on others indicate that they have very slight chances of such development.

Unproductive faulted and terraced areas are present in fields in which similar structural forms are large producers. In no place in the United States is the location of test holes more closely restricted to well developed anticlines than in Wyoming. Yet in a typical year, 1925, only two gas wells and three oil producers were obtained out of a total of 29 wildcat tests completed. As many of the failures were carried to depths of more than 3,000 feet and the productive horizons in nearby structures definitely identified, the lack of success cannot be attributed to failure to carry the tests to sufficient depths.

In some cases the absence of oil in such areas can be traced to loss through outcropping portions of productive horizons. This is undoubtedly the cause of the non-productivity of the Powder River anticline in Wyoming. This structure is only about 15 miles to the northwest of the productive Salt Creek structure. It has a closure of about 1,300 feet and in many respects shows close similarity to its neighbor. Seepages of oil have been known for many years, but no commercial production has been developed despite the drilling of tests to as great a depth as 3,465 feet. Practically the same formations are present as have been found to be productive at Salt Creek. One distinction is of major importance. At Salt Creek none of the formations below the Montana group of the Cretaceous has been exposed by erosion. At Powder River all of the formations down to the Jurassic appear on the flanks or the crest of the anticline. Thus the productive horizons at Salt Creek have been exposed to loss through seepage at Powder River.

In other areas the absence of oil is more difficult to understand. As the productive horizons do not outcrop within the drainage area of the structure, loss of oil through outcrop seepages does not appear possible. In some instances the loss of the oil may be attributed to escape through vertical fissures. In others the flushing action of artesian waters may have removed the oil despite the large size of the folds. Though their identification is difficult, it appears that in many cases the dynamic action causing the development of the folds did not become effective until after the formation of the oil. Folds of such origin would naturally have no effect in retarding the migration and escape of the oil created before their development.

The presence of oil or gas in commercial quantities in any given area cannot be considered as due solely to the structural conditions now existing in that area. Neither can it be considered as due entirely to the more general underlying conditions which would logically favor the formation and existence of petroleum or natural gas. In every case in which quantities sufficient to make commercial recovery possible are present, their presence indicates a favorable combination of both types of factors.

AUTHOR INDEX

Abraham, H., 52
Alden, W., 167
Alderson, V., 52
Ambronn, R., 496
Anderson, J., 20
Andrews, E., 188
Armstrong, R., and Rader C., 428
Arnold, R., with Eldridge G., 336
Arnold, R., and Johnson H., 306, 307, 335, 337
Ashley, G., 51
Aurin, F., with Clark G., 465
Aydelotte, J., with Gavin M., 46

Bacon, R., and Hamor, W., 13
Barton, D., 379, 381, 388, 407, 486, 496
Barton, D., and Paxson, R., 392
Bartram, J., and Roark, L., 439, 441
Bartram, J., and Wilson, J., 490, 492
Bauer, C., 444, 446, 447
Beal, C., 458, 459, 460, 461
Becker, G., 61, 159
Bell, H. S., 21, 27
Bell, H. W., 203, 291
Berger, W., 363, 364
Berthelot, M., 55, 56
Bertrand, C., and Renault, B., 66
Bevier, G., 393
Blackwelder, E., 158
Blatchley, R., 417, 419
Böckh, H., 381
Bone, W., with Jerdan, D., 55
Bonine, C., 342
Bownocker, J., 342
Bradley, W., 71
Bradenthaler, E., and Campbell, P., 203
Bransky, O., and Gilpin, J., 77
Briner, E., with Wrocynski, A., 55
Brown, J., and Dake, C., 231
Brucks, F., 317, 318, 319
Brun, A., 57
Busk, H., and Mayo, H., 451
Buttram, F., 458
Bybee, H., and Short, R., 372

Cadman, W., 362
Calder, W., 357
Campbell, P., and Bradenthaler, E., 203
Case, J., 254, 255
Case, J., and Keyes, R., 257, 258
Chamberlin, T., and Salisbury, R., 114, 158
Clapp, F., 294, 428, 431, 432, 433
Clark, G., 465, 467, 468, 470
Clark, G., and Aurin, F., 465
Clark, S., 471, 472, 473, 474
Clarke, F., 41, 54, 62, 114, 182
Cloëz, S., 54, 55, 56
Collier, A., 211, 287, 288, 289
Collingwood, D., and Rettger, R., 371, 372, 373
Collom, E., 219
Condit, D., 285
Condit, D., and Mills, R., 286
Coste, E., 57
Cox, H., Dake, C., and Muilenburg, G., 231
Craddock, W., with Hudson, F., and Taliaferro, W., 329, 332
Cross, R., 41, 44, 52
Cunningham, G., 264
Cunningham-Craig, E., 13, 47, 87

Dake, C., and Brown, J., 231
Dake, C., with Cox, H., and Muilenburg, G., 231
Daly, M., 189, 201
Danby, A., 52
Daniell, A., 160
Darton, N., 210
Darton, N., with Washburne, C., 366
Davis, I., 45
Day, D., 13, 76, 77
Day, W., 62

DeGolyer, E., 58, 369, 370, 388, 401, 407
Denison, A., 442, 443, 444
Deussen, A., 145, 177, 315
DeWolf, F., 229
Dodd, H. V., 260, 261
Dubendorf, H., with Overbeck, R., and Schwennsen, A., 257, 259

Eaton, J., 151, 260
Edson, F., 489
Egloff, J., and Rittman, W., 23
Eldridge, G., 324, 330
Eldridge, G., and Arnold, R., 336
Ellis, A., 165
Emmons, W. H., 13, 82
Engler, C., 62, 63, 64
Engler, C., and Höfer, H., 28, 29, 30
English, W., 254, 324, 325, 335, 336
English, W., with Kew, W., 328
Estabrook, E., 266
Estabrook, E., and Rader, C., 428
Estabrook, E, with Young, H., 184, 428

Fath, A., 454, 456, 457, 458
Fath, A., and Moulton, G., 276, 277
Fenneman, N., 406
Fettke, C., 171
Fuller, M., 111, 124

Gardner, J., 458
Garfias, V., 13
Garner, A., 154
Gavin, M., 48, 52
Gavin, M., and Aydelotte, J., 46
Gilpin, J., and Bransky, O., 77
Goode, H., 329
Goldman, M., 106, 407
Golubiatnikov, D., 157
Grabau, A., 114, 158
Gregaeris, R., 52
Griswold, W., 190
Gutenberg, B., 496

Hager, D., 13, 420
Hager, L., 396, 397, 406
Hahn, H., 54, 55, 56
Hamor, W., with Bacon, R., 13
Hancock, E., 290
Harris, G., 397, 398, 399, 406
Hayes, C., 231
Hayes, C., and Kennedy, W., 407
Heald, K., and Mather, K., 239
Heald, K., with Wegemann, C., 439
Heiland, C., 496
Henderson, J., 70
Hewett, D., 266, 267
Hewett, D., and Lupton, C., 243, 266, 268, 296
Hill, H., and Sutton, C., 312
Höfer, H., and Engler, C., 28, 29, 30
Hopkins, O., and Matson, G., 203, 312
Hopkins, O., Powers, S., and Robinson, H., 141
Hosterman, J., 465
Hudson, F., 331, 335
Hudson, F., with Taliaferro, N., and Craddock, W., 329, 332
Huguenin, E., 423, 424
Hull, J., 280
Hume, W., 449
Hunt, J., 188
Hunter, C., 146
Huntley, L., with Johnson, R., 13
Huntley, L., and Mason, S., 152
Huntley, S., 383, 384, 407

Jeffrey, E., 66
Jerdan, D., with Bone, W., 55
Johnson, D., 114
Johnson, H., and Arnold, R., 306, 335, 337
Johnson, R., 189, 200
Johnson, R., and Huntley, L., 13

Kaiser, C., 264, 265
Kay, F., 417, 418
Kennedy, W., 404
Kennedy, W., with Hayes, C., 407
Kew, W., 327, 329, 334
Kew, W., and English, W., 328
Keyes, R., with Case, J., 257, 258
Kirwan, M., 225
Knapp, A., 218
Krampert, E., 276, 278

Lahee, F., 231, 248, 312, 313, 314, 315, 316
Lahee, F., with Pratt, W., 311, 312
Larsen, E., 177
Lee, W., and Lupton, C., 434
Lehman, T., 62
Leith, C., 250
Leith, C., and Mead, W., 114
Lesquereux, L., 63, 65
Lewis, J., 170, 428, 432
Lilley, E., 10, 13, 110, 112, 113, 476
Lobeck, A., 231
Lovejoy, J., 462
Lupton, C., 295
Lupton, C., and Lee, W., 434
Lupton, C., and Hewett, D., 243, 266, 268, 296

Mabery, C., 31, 59
MacFarlane, J., 64
Madgwick, T., and Thompson, B., 157
Marcusson, J., 62
Mason, S., 382
Mason, S., with Huntley, L., 152
Mather, K., and Heald, K., 239
Matson, G., 312
Matson, G., and Hopkins, O., 203, 312
Matteson, W., 407
Mayo, H., and Busk, H., 451
McCollom, C., with Templeton, R., 254
McCoy, A., 73, 74, 75, 190, 199
McDonald, W., 279
McKee, J., 45, 52
McLaughlin, R., 230
Mead, W., with Leith, C., 114
Meinzer, O., 92, 115, 136, 162, 168
Melcher, A., 170, 179, 350, 353
Mendeléef, D., 54, 56
Miller, W., 114, 117, 149, 158
Mills, E., 45
Mills, R., 190, 191, 196, 197
Mills, R., with Condit, D., 286
Mills, R., with Robinson, H., 283, 284, 353
Mills, R., and Wells, R., 182, 203
Milner, H., 497
Miser, H., and Purdue, A., 221
Moissan, H., 54, 56
Monnett, V., 236
Moore, E., 50, 52
Moore, R., 132, 455
Moore, R., and Plummer, F., 134, 245, 246
Moulton, G., with Fath, A., 276, 277
Mrazac, L., 189, 201, 381
Muilenburg, G., with Dake, C., and Cox, H., 231
Munn, M., 189, 192, 193, 194, 195, 198, 207
Munn, M., and Shaw, F., 227, 354

Newberry, J., 188
Norton, W., 92
Nowels, K., 274, 275

Ochsenius, C., 69
Orton, E., 120, 174, 189, 203
Overbeck, R., with Schwennsen, A., and Dubendorf, H., 257, 259

Pack, R., 172, 241, 301, 302, 303, 305
Paige, S., 231
Palmer, C., 32
Panyity, L., 13
Papp, K., 381
Pascoe, E., 263
Patton, L., with Sellards, E., 436, 437, 438
Paxson, R., with Barton, D., 392
Pautsch, E., 496
Peterson, C., 130
Phinney, A., 174
Pirsson, L., and Schuchert, C., 114, 158
Plummer, F., and Moore, R., 134, 245, 246
Ports, P., and Shaw, E., 271
Powers, S., 386, 407, 439, 440, 449, 451, 462, 475, 478
Powers, S., with Hopkins, O., and Robinson, H., 141
Pratt, W., 444
Pratt, W., and Lahee, F., 311, 312
Purdue, A., with Miser, H., 221

Rader, C., with Armstrong, R., 428
Rader, C., with Estabrook, E., 428

Rae, C., 71
Ramsey, W., 60
Redfield, A., 374
Redwood, B., 13
Reeves, F., 104, 140, 217, 294, 414, 415, 416, 434, 435
Reger, D., 122
Renault, B., with Bertrand, C., 66
Rettger, R., with Collingwood, D., 371, 372, 373
Rich, J., 198, 359, 360, 361
Richardson, R., 155, 451, 452, 453
Rittman, W., and Egloff, J., 23
Roark, L., and Bartram, J., 439, 441
Robinson, H., with Hopkins, O., and Powers, S., 141
Robinson, H., and Mills, R., 283, 284, 353
Robinson, H., with Shaw, E., 272
Rogers, G., 52, 60, 65, 186, 203, 342, 343, 344, 407
Rogers, R., 355, 356
Ross, C., 272, 273, 284, 285
Rubey, W., 297, 298, 299

Sabatier, P., and Senderens, J., 55
Salisbury, R., with Chamberlin, T., 114, 158
Salisbury, R., and Willis, B., 158
Salvadori, R., 55
Sands, J., 350, 351, 352
Schlicter, C., 159, 161
Schuchert, C., 121, 131, 143, 158
Schuchert, C., with Pirsson, L., 114, 158
Schwennsen, A., Overbeck, R., and Dubendorf, H., 257, 259
Sellards, E., 317
Sellards, E., and Patton, L., 436, 437, 438
Senderens, J., with Sabatier, P., 55
Shaw, E., 198, 271, 320, 321, 323
Shaw, E., and Munn, M., 227, 354
Shaw, E., and Ports, P., 271
Shaw, E., and Robinson, H., 272
Shayes, F., with Stroud, B., 291
Short, R., with Bybee, H., 372
Shultz, A., 270
Silvestri, O., 57
Small, W., 477
Smith, C., 346
Sokoloff, N., 56
Spielmann, P., 52
Spooner, W., 385, 407
Stadler, S., 62, 63
Stadnichenko, T., 73
St. Clair, S., 320
Stebinger, E., 203
Steiger, G., 55
Stigand, I., 13, 65
Stille, H., 378, 407
Stone, R., 95
Storer, F., 62
Stroud, B., and Shayes, F., 291
Stuart, M., 13, 69, 72, 87
Suman, J., 390, 497
Sutton, C., with Hill, H., 312

Taliaferro, N., Hudson, F., and Craddock, W., 329, 332
Tarr, W., 61
Templeton, R., and McCollom, C., 254
Thiessen, R., 66
Thom, W., 242
Thompson, A., 13, 72, 102, 263, 357, 423, 450
Thompson, A., and Madgwick, T., 157
Thomson, F., 61
Trager, E., 73, 74, 142
Truex, A., 425, 426, 427
Twenhofel, W., 114

Uren, L., 497

Van der Gracht, W., 394, 407
Van Hise, C., 161
Van Horn, F., 203
Voitesti, I., 392, 407

Warner, C., 231
Warren, C., 62
Washburne, C., 59, 189, 198, 367
Washburne, C., with Darton, N., 366
Watts, W., 65
Wegemann, C., 213, 428, 429, 430, 431

Wegemann, C., and Heald, K., 439
Wells, R., with Mills, R., 182, 203
Westcott, H., 52
White, D., 72, 111
White, I., 8, 189
White, L., 118, 119, 125, 126, 130
Williams, F., 54, 55, 56
Willis, B., 74, 149, 158, 237, 250
Willis, B., and Salisbury, R., 158
Wilson, J. 292
Wilson, J., with Bartram, J., 490, 492
Wilson, W., 346, 347, 348, 349
Winchell, A., 188
Winchester, D., 52, 67
Wrocynski, A., with Briner, E., 55

Young, H., and Estabrook, E., 184, 428

Ziegler, V., 13
Zoloziecki, R., 69

SUBJECT INDEX

A

Accumulation of oil and gas
  complex types, 408
  controlled by porosity, 339
  in faulted rocks, 309
  in fissures, 365
  in folded rocks, 251
  in igneous rocks, 368
  in salt core structures, 376
  study of, 5
  theory of, 181
Acetylene series, 26, 27
Aclinal structures, 232
Aerobic bacteria, 70
Africa, salt domes in northern, 376
Aging of oils, 78, 79
Akita district, 374
Alaska, 137, 139
Alberta, 44, 138
Albertite, 37, 43, 86, 485
Algae, as sources of oil, 66
Algal coals, 52
Algeria, 147
Alidade, use of 215
Alignment of folds and faults, 239
Alipathic compounds, 25, 27
Aluminum chloride, 78
American Petroleum Institute scale, 17
Anerobic bacteria, 70
Aneroid barometers, use of, 215
Anhydrite
  in relation to occurrence of oil, 97
  in salt dome caps, 402
Animals, as sources of oil, 64
Anthracene series, 26, 30
Anthracite, 37, 50
Anticlinal terraces, 282
Anticlinal theory, see gravitational theory
Anticlines and Anticlinal Folds
  broad, 244, 290
  buried, 436
  complex, 439
  faulted, 423
  having porosity variations, 414
  inclined asymmetrical, 262
  plunging, 281
  quaquaversal, 271
  salt, 378
  simple symmetrical, 253
  upright asymmetrical, 257
  value as oil producers, 306, 308
  with curved axes, 266
  with divided axes, 269
Appalachian field and geosyncline
  age of oil, 121, 125, 127, 133
  character of oil, 1, 19, 27, 34
  extent of, 11
  geological sections of 122, 124, 323
  natural gas, 39, 203
  pools in, 322, 354
  waters of, 182
  see also Kentucky, Ohio, New York, Pennsylvania, Tennessee, West Virginia.
Apsheron Peninsula, 156, 157
  see also Baku
Arcadia salt dome, 385
Archeozoic age, 115
Argentina, 4
  age of oil, 139, 147
  character of oil, 18, 20, 31, 34
  geologic section, 146
Arkansas, 6, 13
  age of oil, 148
  geologic sections, 224, 280
  natural gas, 38, 39
Arkose sandstone, 94
Aromatic compounds, 25
Arrangement of particles, effect on porosity, 163
Asphalt, natural, 2, 15, 37
  as a cause of accumulation of oil, 304, 306

  characteristics, 40, 41
  formation, 85
  in exploration, 484
Asphalt, refinery, 41
Asphalt sealed traps, 304
Asphaltic base oil, 2, 32, 37, 113
Asphaltic bitumens, 37, 85, 484
Asphaltic limestone, 37, 44
Asphaltic rocks, 37, 44, 85, 484
Asphaltic sandstone, 37, 44
Asphaltites, 2, 37
  characteristics, 42
  formation, 85
  in exploration, 484
Assortment of particles, effect on porosity, 163
Asymmetrical folds, 252
  upright, 257
  inclined, 262
Athabasca tar sands, 44, 85, 485
Athens—Rosecrans, 411
Augusta pool, 454, 456
Australia, 45
Axial planes, 251
  curved, 266
Axis of a fold, 251

B

Bacon Rind anticline, 284
Baicoi, 382
Baku district, 7, 156, 423
Balcones fault zone, 248, 310, 311, 312, 373
Bald Hill Dome, 272, 284, 285
Barbados, 156
Barber's Hill, 391
Barsdale pool, 331
Bartlesville or Glenn Sand, 273, 283, 284, 297, 345, 348, 350, 458
Base of oils, 1, 32
Basin field, 295
Batson, 391
Baume scale, 17
Bend Arch, 11, 104, 244, 245, 246, 290, 414
Bend shales, 104
Benton shales, 104
Benzene series, 1, 26, 29, 30
Bermudez asphalt lake, 40, 41
Beverly, 411
Bibliographies
  general, 13
  geologic mapping and representation of structures, 231
  geophysical methods, 496
  natural gas and bitumens, 52
  physical geology, 114
  regional and historical geology, 158
  salt core structures, 406
  structural geology, 250
Big Creek, 391
Big Horn Basin, 11
  formations in, 268
  producing areas, 267, 295
  structure of, 243, 244
Big Lake, 436
Big Sinking pool, 322
Binagadi pool, 423
Biochemical stage of oil generation, 72
Bitumen, generation of, 75
Bitumens and bituminous substances
  character, 36
  formation, 84
  use in exploration, 484
Bituminous coal, 37, 48, 50
Bituminous limestone, 44
Bituminous residues
  character, 37, 40
  distribution, 484
  formation, 84
  in exploration, 484
Bituminous rocks, 44, 85, 484
Bituminous sandstones, 44, 85, 484
Bituminous schists and marbles, 37
Black Hills uplift, 287
Blue Ridge, 386, 391
Boggy Creek, 385
Boghead coal 37, 45, 51, 52, 66
Boling, 391
Borneo, 18, 40, 102
Bowlegs, 11, 463
Bradford sand, 179
Brea, 37, 42
Brea-Canyon-Olinda pool, 324, 328, 329
Brea grit pools, 285, 290
"Breaks," 174, 345

Breccia in salt structures, 382, 394
Brines, oilfield, 181
Bryan Heights, 404
Buena Vista Hills or anticline, 253, 303
Buffalo Basin, 211
Burbank pool, 350
Bureau of Standards scale, 17
Burgess pool, 364
Buried Hills, 412
Buried structure, 412
Burkhart pool, 286
Burma, 11, 27, 156, 263
Burnt shale, 479
Bush City string, 360, 361

C

California, 1, 2, 6, 9, 11, 13, 170
  age of oil, 147, 154, 155, 156
  bitumens, 40, 44, 484
  character of oil, 16, 17, 18, 19, 20, 23, 29, 31, 32, 33, 34
  general structure, 241, 324, 331, 411
  geological sections, 151, 255, 259, 301, 334
  natural gas, 39, 60
  producing areas, 253, 254, 257, 260, 264, 301, 302, 305, 306, 326, 329, 333, 335, 355, 423
Cambrian period
  conditions during, 116
  oil and gas in, 116
Camden uplift, 281
Campina, 382
Campton pool, 322
Canada, 4
  age of oils, 117, 126, 137
  bitumens, 44, 85, 485
  character of oils, 17, 34
Canadian Shield, 115
Cannel City pool, 322
Cannel coal, 3, 37, 50
Canon City Embayment, 366, 367
Capillarity, 22, 160
  as an agency of concentration, 198
  in expulsion of oil from source beds, 190
  in hydraulic theory, 196
  in retention of pressures, 204
  opposed to gravity, 192
Capillary constants, 23
Capillary openings, 160
Capillary theory of concentration, 198
  limitations, 200
  present status, 207
Cap rocks, salt dome, 402
  anhydrite and gypsum in, 402
  limestone in, 403
  oil above, 389, 390
  oil in, 389, 392
  origin of, 402
  sulphur in, 403
Carbide theory, 54, 56
Carbomorphism of coals, 81
Carbonaceous shale, 75
Carbon dioxide, 16, 39
Carboniferous shales of Scotland, 108
Carbon monoxide, 16, 39
Carbon ratio theory, 110
  application, 113
  principles, 111, 113
Carbon residues, 33
Carpathian salt domes, 380
Casing head gasoline, 38
Cat Creek, Montana, 19, 434
Catskill formation, 300, 354
Cement anticline, 293, 294
Cementing, 163
Cenozoic Era
  conditions during, 149
  divisions of, 149
  see also Tertiary
Ceralvo fault, 311
Ceresin, 37, 43
Cerro Azul, 477
Channel deposits
  as oil containers, 358
  formation of, 358
Chapopote, 37, 42
Chattanooga shale, 119, 126, 472
Chemical composition
  of bitumens, 40
  of natural gas, 38
  of oils, 24
Cherokee shales, 104, 133, 342, 347, 348, 350, 360, 364
Chino fault, 324
Cincinnati Arch, 11, 120, 121, 244, 290, 344

Clays
  as retainers, 175
  porosity, 175
  sapropelic, 72, 107
Cleveland gas district, 342, 344
Clinton sand district, 342
Closed folds, 253
Coal, 3, 37, 48
  analyses, 49
  classification, 50
  formation, 81, 100
  in prospecting for oil, 111
  metamorphism and alteration, 81, 109
Coal distillation theory, 67
Coal gas, 37, 38
Coastal swamps, 100
Cochahee domes, 293, 297
Colombia, 4
  age of oil, 147, 155
  character of oil, 20, 34
  geologic section, 152
Colony string, 361
Color
  of oils, 16
  of sediments, 93
Coloradic geosyncline, 142
Colorado, 6
  age of oil, 148
  bituminous substances, 45, 46, 48, 71
  pool in, 366, 367
Columnar sections, typical and use of, 208, 216, 217
Comanchean, see Lower Cretaceous
Compacting
  effect on porosity, 164
  in structure development, 235
  preliminary to folding, 237
Competency of rocks, 237, 240, 409
Competent folding, zone of, 237, 238, 239
Complex structures, 408
Compressional faulting, 249
Concentration of oil and gas, 181
  see also accumulation
Concentric folds, 252
Conglomerates, 173
Contact zones, production from, 375
Container rocks, 159
Contour maps, use of, 212, 213, 214, 231
Conradson carbon residue, 33
Convergence maps, use of, 226, 227, 228
Cores and coring, 221, 223, 497
Corsicana pool, 312
Cotton Valley pool, 279
"Covered Hills," 412
"Covered structure," 411
Coyote Hills oil pool, 230
Cracking, 21, 75, 78
Crest, 251
Cretaceous, see Lower Cretaceous, Upper Cretaceous and Mesozoic
Crevices, production from, 365
Cross sections, use of, 223, 224
Crustal deformation, nature of, 237
Crustal movements, effects on porosity, 166
Crystal growth theory of origin of salt domes, 397
Cuba, 16, 41, 58, 375
Currie, 315
Cushing pool, 20, 244, 290, 293, 454, 458
Cut off basin deposits, 96
Czechoslovakia, 4

D

Dakota formation, 274, 277, 433
Damon Mound, 9, 33, 391, 393
Deep sea deposits, 101
Delaware anticline, 285
Density of oils, 17
Depositional conditions, effect on oil accumulation, 233, 339
Depth, effect on character of oil, 79
Desert deposits, 92
Devonian black shales, 73, 76, 103, 108, 119, 125, 126
Devonian Period
  as a source of oil, 125, 126
  conditions during, 121, 123
  producing areas, 354
Diamond drilling
  method of use, 489

  typical log, 222
  typical maps and sections, 490, 492
  value in prospecting, 220, 492
"Diapir folds," 252, 380
Diastrophic theory of oil accumulation, 189, 201
Diatoms, as sources of oil, 66
Dikes, igneous, 368
Diolefine series, 26, 27
Dip and strike symbol maps, use of, 208, 211, 231
District, defined, 11
Dolomitization, 165
Domes, 269
  quaquaversal, 269
  salt, 376
Dominquez pool, 260, 411
Dropright dome, 459
Drumright dome, 459
Dryholes or failures, 501
Dynamic pressure
  alteration and destruction of oil by, 79, 80
  development of structures by, 237
  generation of oil by, 74
  results of intermittent, 412

E

Earlsboro pool, 11, 463
Eastern Province, 3, 10, 12
  age of oil, 119, 120, 126, 133
  map showing relation of oil and gas to coal, 110
  see also Illinois, Indiana, Kentucky, Michigan, New York, Ohio, Pennsylvania, Tennessee, West Virginia
East Indies, 4
  age of oil, 156
  character of oil, 17, 19, 29
  geologic section, 102
Ecuador, 4
Edgerly, 386, 391
Edwards limestone, 141, 318
Egypt, 4
  age of oil, 147, 156
  geologic section, 450
  pools in, 449
Elaterite, 37, 43
Eldorado, Arkansas, 224
Eldorado, Kansas, 39, 60, 456
Electric methods of exploration, 493
Elk Hills anticline, 253
Elsinore fault, 324
En échelon faults, 239
England, 51
Eocene, 149, 150, 153, 155
  see also Tertiary
Epeiric sea deposits, 101, 106, 107
Epicontinental shelf deposits, 101
Estill County, Kentucky, 323
Ethylene series, 26
Evaporation of oils, 84
Expansion, coefficient of, 20
Exploration, 479
  by field geologist, 208
  geophysical methods, 493
  in areas having no surface indications, 487
  limitations, 499
  policies, 499
  use of subsurface methods, 497
  use of surface indications, 480
  with diamond drill, 489
Expulsion of oil from non-porous rocks, 190

F

Failures or dry holes, 501
Faults and faulting
  causes, 247
  normal or gravity, 247, 309
  overthrust, 335
  relation to folds, 410
  reverse or compressional, 249, 309
  size and intensity, 248, 249, 309, 409
Fault structures, 309
  development of, 235
  types, 309, 310
  value, 234, 309, 338
Fellows, pool near, 305, 306
Flank sands, 389
Florence, Colorado, 367
Flowage experiment, 73
Fluorescence in oils, 16
Field, defined, 11

Filtration of oils, 76
Fish, as source of oil, 64
Fissure seepages, 487
Fissures, production from, 365
Fitchburg pool, 322
Folded structures
  characteristics, 251
  development, 235
  value of, 234, 306
Folds and folding
  differences in competency, 240, 409
  differential compacting, 235
  dynamic action, 237
  horizontal thrust, 240
  period and duration, 408, 409, 412
  relation to faulting, 410
  salt core types, 376
  types, 251
  vertical uplift, 244
Foraminifera, source of oil, 65
Formosa, 4
Foxburg quadrangle, 227, 354
Fox-Bush-Eastman area, 365
Fracture, zone of, 237
France, 4, 44
Furbero pool, 369

G

Galicia or Poland, 4
  age of oil, 147, 155, 156
  character of oil, 21, 27
  ozokerite, 42, 85
Garnett shoe string, 360
Gas, natural, 2
  composition, 38
  effects on viscosity and surface tension of oil, 201
  function in accumulation of oil, 200
  generation of, 76, 82
  pressures, 202
  solubility in oil, 201
Gas seepages
  in exploration, 481
  location of, 482
Geanticlines, 244, 291, 308
Gemsah, 449
Geochemical stage, 72
Geologic activity, limitations of, 499
Geologic history in relation to occurrence of oil, 115
Geologic recommendations, basis of, 5
Geology, utilization of, 7
Geophysical prospecting, 493
  methods, 493
  results, 495
Geosynclines
  oil from, 300
  structure, 244
German salt core structures
  cap rock, 402
  location, 376
  mechanics of uplift, 395, 400
  origin, 392, 394
  size, 379
  structure, 377
Germany, 4, 44, 139
Gilsonite, 37, 42
Glacial deposits, 91
Glance pitch, 37, 42
Glauconite, 101
Glenn pool, 9, 341, 346
Glenn sand, see Bartlesville sand
Glenn shales, 133
Globe anticline, 302
"Golden Lane" of Mexico, 475
"Golden Lanes" of Kansas, 362
Goodrich-Parker string, 362
Goose Creek, 386, 391
Grahamite, 37, 42
Granite ridge, 453
"Granite wash," 375, 445
Graphic well logs, 219
Graphitic anthracite, 81
Grass Creek, 266
Gravimetric methods of exploration, 493, 494
Gravitational theory, 3, 7, 8, 187
  history of, 188
  manner of accumulation, 190
  objections to, 192
  present status, 207
Gravity or normal faulting, 247, 309
Great Britain, 133
Green River shales, 45, 46, 70, 71, 107, 108, 150
Greenwood County, Kansas, 362

Gulf Province, 12
  see also Gulf Coast Salt Dome Field, Texas, Louisiana and Arkansas.
Gulf Coast Salt Dome Field, 376
  age of salt, 395
  cap rock in, 402
  mechanics of uplift, 395, 400
  oil from, 389, 391
  origin of salt, 395
  period of uplift, 401
  use of geophysical methods, 495
Gypsum
  in relation to occurrence of oil, 97
  in salt dome caps, 402

H

Hanover district, salt structure in, 378
Haynesville, 279
Healdton, 23, 34, 355, 439
Heat
  function in oil alteration, 78
  function in oil generation, 72
Helium, 16, 40, 60, 61
Herridge plunging anticline, 283
Hills, buried and covered, 412
Hogback, 9, 19, 274
Hogshooter gas pool, 364
Hogshooter shoe string, 362, 363
Homer, 279
Horizons of varying porosity, 345
Horizontal thrust structures, 240
Hubbard pool, 425
Hull, 391
Humble, 380, 389, 391
Humid areas, deposits of, 97
"Hunch" locations, 7
Hundred foot sand, 203, 345, 354
Huntington Beach, 257, 411
Hurghada, 449
Hybrid rocks, 176
Hydraulic theory, 194
  capillarity in, 196
  criticism of, 196
  manner of accumulation, 195
  modification of, 198
  present status of, 207
Hydrogen, 16, 38, 39, 78, 82
Hydrocarbons, 1, 15
  alteration of, 77
  classification and properties, 25
  destruction of, 82
Hydrogenatian, 76, 78
Hydrogen sulphide, 15, 17, 39, 40, 59, 83
Hydrostatic pressure, 202

I

Igneous origin of oil, see inorganic theories
Igneous origin of salt domes, 396
Igneous rocks
  as containers of oil, 57, 58, 177, 234, 368, 375
  as indicators of oil, 90
  competency of, 240
  porosity of, 177
Illinois, 6
  age of oil, 127, 133
  character of oil, 19
  producing area in, 417
India, British, 4, 11, 42
  age of oil, 156
  pools in, 263
Indiana, 6
  age of oil, 121, 127
  bituminous substances, 45, 48
  natural gas, 39
  oil pools in, 417
  see also Cincinnati Arch
Inglewood fault or uplift, 257, 411, 424
Inglewood pool, 411, 423
Initial production, map showing, 299
Inorganic theories, 54
  application, 55
  evidence supporting, 57, 58
  insufficiency of, 62
Interior Gulf Coast Salt Domes, 384
  characteristics and structure, 385, 386
  oil in, 385
Interstices, nature of rock, 162
Iodine, 65
Iowa, 38, 92
Isochor lines, 228
Isomers, 26, 27

Iso-pachous lines, 228
Isopach map, typical, 349
Isovols, 113
Isthmuthian domes of Mexico, 383
Italy, 4, 44, 147, 155
Irvine oil pool, 320, 322
Irvine-Paint Creek fault, 320

J

Japan, 4, 31, 58
  age of oil, 156
  geologic section, 374
  producing areas in, 374
Java, 57
Jennings, 391
Jointing, effects on porosity, 165, 167
Jurassic Period, 138
  conditions during, 138
  oil horizons of, 139
  producing areas, 383, 420

K

Kansas, 1, 6
  age of oil, 127, 133
  character of oil, 27, 33
  geologic section, 128, 130
  granite ridge of, 453
  natural gas, 39, 40, 60, 61
  producing areas in, 359, 362, 365, 454, 456
Kay County, Oklahoma, 425, 465, 471
Kentucky, 6
  age of oil, 119, 121, 127
  bituminous solids, 44, 45, 46, 51, 71
  character of oil, 19
  geological section, 323
  natural gas, 39
  producing area, 320
Kentucky River fault, 320
Kerogen and Kerogen shale, 2, 37
  formation and alteration, 65, 70, 72, 107
  nature of, 44, 47, 72, 87, 107
  solubility, 46
Kevin-Sunburst, 31, 420
''Knife edge'' structure, 475
Kosse, 315

L

Laccolithic domes, 368, 375
Lake deposits, 99
Lamb anticline, 294, 295
Land locked basins in deposition of oil source beds, 106
La Salle pool and anticline, 229, 246, 291, 339, 417
Lateral or flank sands, 389
Lensing sands, 341
Levelette terrace, 283
Lignite, 37, 50
Lima, Ohio, 20, 34
Lima Indiana district, 17, 119
Limestones, 173
  as containers, 173
  as retainers, 174
  as source beds, 103, 105
  cap rocks, 403
  competency, 240
Little River, 11, 463
Local structure, 233, 489
Lockhart, 58, 370
Lockport, 391
Loess deposits, 94
Logs, see well logs
Long Beach, 9, 34, 257, 260, 262, 411
Los Angeles Basin
  general structure, 324, 336, 411
  geologic sections, 151, 255, 259
  producing areas in, 254, 257, 260, 324, 326, 329, 423
Los Angeles fault, 336
Lost Soldier dome, 276
Louisiana, 6, 12, 170
  age of oil, 141, 148, 155, 156
  character of oil, 20
  Gulf Coast domes, 386
  interior salt domes, 384
  natural gas, 38, 39, 60, 203
  northern portion, geologic section, 280, pools in, 279, 291
Lower Cretaceous
  history, 139
  oil in, 141
  producing areas in, 318, 422, 428, 436, 475
Luling fault and pool, 9, 141, 312, 317, 371, 373
Luling-Mexia, fault zone, 310, 311
Lyons-Quinn pool, 225
Lytton Springs, 371

M

Madison limestone, 139, 422
Magnetic irregularities in oil fields, 61
Magnetic methods of exploration, 493, 494
Maidan-I-Naftun, 451
Maikop pool, 65, 357
Maltha, 37, 41, 42
Manjak, 37, 42
Maps and mapping
  contour, 212
  convergence, 226
  errors in, 214
  problems in, 489
  sand or isopach, 228
  strike and dip, 211
  subsurface, 225
  surface geology, 209
Maracaibo basin, 11
Marathon fold, 244
Marble falls limestone, 345, 414
Maricopa shales, 303, 305, 357
Marine animals as sources of oil, 65
Markham, 388
Marsh gas, 37, 38
McKittrick formation, 337, 357
McKittrick overturned fold, 306
McKittrick thrust fault, 335
Mechanical flow, zone of, 237
Menilithic shales, 64
Mesozoic Era and Rocks
  conditions during, 137
  distribution of oil, 148
  producing areas, 266, 274, 276, 279, 287, 295, 312, 317, 368, 370, 377, 420, 428, 434, 449, 475
Metamorphic Rocks
  as containers of oil, 177
  as sources of oil, 108
  porosity, 177
Metamorphism
  function of, 107
  in coals, 109
Methane, 25, 26, 38
Mexia district, 9, 11, 312
Mexia fault zone, 311, 312
Mexia-Groesbeck gas pool, 170, 313
Mexia-Luling fault zone, 248, 310
Mexia pool, 312, 320
Mexican salt structures, 376, 383
  age of salt, 394
  mechanics of uplift, 400
  oil in, 384
  structure, 384
Mexico, 4, 58, 383, 476
  age of oil, 141, 147, 155
  bitumens 40, 484
  character of oil, 16, 17, 18, 20, 22, 27, 31, 33, 34
  geologic sections, 142, 478
  producing areas, 366, 369, 384, 475
Michigan, 6
Micos Cañon fault, 311
Mid-Continent Province, 3, 12, 132
  age of oil, 118, 119, 126, 128, 130, 133, 135
  general structure, 132, 239, 290, 453
  geologic sections, 97, 128–130, 134, 217, 437, 464
  producing areas, 271, 272, 283, 284, 294, 297, 346, 350, 353, 359, 362, 363, 414, 425, 439, 442, 444, 456 458, 462, 465, 471
  relations between coal, oil and gas in, 112
Midway-Spellacy anticline, 301, 302
Midway Valley syncline, 301, 302, 305
Migration of oil, 232
Mine gas, 37, 38
Mineral tar, 37, 42
Mineral wax, 15, 37, 42
Minnesota, 38
Minor faults, 248
Miocene rocks and epoch
  conditions during, 149
  oil in, 155
  see also Tertiary
Mississipian Period
  conditions during, 126, 440
  oil in, 127
  producing areas in, 273, 284, 285, 298, 345, 417
Mississippi lime, 127, 273, 283, 345, 348
Missouri, 44
Mixed base oil, 32, 37

Models, use of, 228, 229, 231
Molecular flow, zone of, 237
Monroe gas area, 38, 203, 291
Montana, 6, 11, 203
  age of oil, 135, 141, 148
  character of oil, 19, 31
  geologic sections, 140, 421
  producing areas in, 420, 434
Montebello pool, California, 331
Monterey shales, 66, 103, 337
Moreni, 382
Mountain folds, relation to oil structures, 241, 243
Mount Pleasant dome, 459
Mud volcanoes
  location, 484
  use in exploration, 483

N

Naphthene base oil, 32, 37
Naphthene series, 1, 25, 26, 29
Natural gas, 15, 37
  characteristics, 38
  concentration of, 181
  destruction of, 82
  generation of, 75
  in alteration of oil, 77
  in migration of oil, 200
  pressures, 203
Natural gas gasoline, 38
Nemaha mountains, 453
Netherlands East Indies, 4
Nevada, 45
New areas, exploration in, 479
Newfoundland, 117
New Mexico, 6, 9
  age of oil, 135, 148
  character of oil, 16, 19
  producing area, 274
Newport, 411
Newport-Beverly Hills fault
  zone—see Inglewood fault zone
New York, 6, 16
  age of oil and gas, 117, 121, 126
Nickel in oil, 16, 32, 60, 78
Nigger Creek, 312
Nitrogen in oil and gas, 2, 15, 16, 31, 39
  origin of, 59, 60, 61
Non-producing structures, 500
Normal faults, 247, 309
North America
  geologic history and occurrence of oil in, 115–158
  paleogeographic maps of, 121, 131, 143, 149
  see also the several states and countries
North Mid-Continent field, 11
''Nose'' structure, 282
Nova Scotia, 117
Nummulithic, 152

O

Oak Ridge fault and anticline, 329, 331
Occurrence of oil and gas, conditions limiting, 89
Odor in oils, 16
Ohio, 6, 11
  age of oil, 119, 121, 127
  character of oil, 19, 20, 34
  general structure, 120, 121, 244, 290, 343
  geologic section, 344
  natural gas, 39, 40, 61, 203
  producing areas, 285, 342
Oils, 1
  chemical properties, 24
  concentration of, 181
  origin and alteration, 53
  physical properties, 15
Oil seepages
  in exploration, 480
  location, 480
Oil shale, 37, 44
  see kerogen shale
Oklahoma, 1, 6, 9
  age of oil, 118, 120, 127, 128–130, 133, 141
  bituminous solids, 44, 485
  character of oils, 16, 20, 23, 27, 34
  geologic sections, 128–130, 464
  granite wells, 454
  natural gas, 39, 60, 61, 203
  productive areas, 272, 283, 284, 294, 297, 346, 350, 353, 362, 363, 425, 439, 442, 445, 458, 462, 465, 471

Old Woman Creek anticline, 210
Olefine acetylene series, 26
Olefine series, 1, 26, 27
Olefine terpenes, 26
Oligocene
  conditions during, 149
  oil in, 155
  see also Tertiary
Olinda pool, 324, 329
Ontario, 19, 31, 34, 121
Open chain compounds, 25
Open folds, 253
Openings in rocks, 160, 161
Optical activitiy of oils, 24
Orange, 386, 391
Ordovician Period
  conditions during, 117
  oil in, 118, 119
  producing areas. 425, 440, 443, 456, 458, 462, 465, 471
Organic debris, conditions favoring deposition, 105
Organic theories of origin of oil, 3, 62
  alteration of oils and gases, 76
  application to search for oil, 89
  conversion to solids, 84
  deposition and accumulation, 68
  destruction of hydrocarbons, 82
  experimental proof, 62
  nature and alteration of kerogen, 72
  nature of oils and gases, 76
  source materials, 64, 68
  summary, 86
Origin of petroleum and natural gas, 53
Osage County, Oklahoma, 9, 127
  general structure, 239
  producing areas, 272, 283, 284, 350, 353
Osage pool, Wyoming, 20, 31, 287, 290
''Outbreaks,'' 380
Outcrop seepages, 487
Overthrust faults, 335
Overturned folds, 252, 305
Oxygen in oil and gas, 15, 16, 31, 39
Ozokerite, 15, 37, 42, 85

P

Pacific Province, 12
  see also California
Paint Creek fault, 320
Paleocene, 149
Paleontology, use in exploration, 497
Paleozoic Era
  conditions during, 116
  importance in oil formation, 136
  producing areas, 271, 273, 284, 294, 297, 320, 342, 346, 350, 353, 354, 359, 362, 363, 414, 417, 425, 436, 440, 443, 444, 456, 458, 462, 465, 471
Panhandle area of Texas, 19, 135, 291, 355, 375, 444
Panuco district, 18, 142, 366, 476
Paraffin base oil, 1, 32, 37
Paraffin dirt, 486
  use in exploration, 486
Paraffin series, 1, 25, 26, 27, 28
Paraffin soil, 37, 42
Peat, 37, 50
Peg models, 229, 230, 231
Pennsylvania, 3, 6, 7, 8
  age of oil, 124, 126, 133
  character of oil, 16, 19, 20, 22, 23, 29, 34
  geologic sections, 124
  natural gas, 39, 203
  producing areas, 179, 193, 354
Pennsylvanian Period
  conditions during, 131
  oil in, 133
  producing areas in, 271, 273, 284, 294, 297, 346, 350, 353, 359, 362, 363, 414, 417, 425, 440, 455, 458, 465, 471
Permian Period
  conditions during, 133
  oil in, 97, 135
  producing areas in, 271, 294, 436, 443, 444
Pershing pool, 294, 297, 301
Persia, 4
  age of oil, 156
  character of oil, 18, 29
  geologic section, 155
  producing areas, 451
  salt structures, 376

Peru, 4
  age of oil, 155
  character of oil, 20, 27, 33, 34
Petrolenes, 42
Petroleum, 1
  chemical properties, 24
  concentration, 181
  conversion to solids, 84
  destruction, 82
  origin and alteration, 53, 111
  physical properties, 15
Petroleum bitumens, 37
  see also petroleum residues
Petroleum geologist, training, 8
Petroleum geology, science of, 3
Petroleum residues, 484
  use in exploration, 484
Petrolia, Ontario, 17, 34,
Petrolia, Texas, 33, 39, 40, 60, 271
Petrology, use in exploration, 497
Phosphoria formation, 45
Phosphorus, 16, 32, 45
Photographs, use of, 208, 209
Physical properties of oils, 16
Piedmont zone deposits, 98
Pierce Junction, 391
Pitch Lake, Trinidad, 40, 484
Plane table, use of, 215
Plaster models, use of, 228, 231
Plastic flow theory of origin of salt structures, 399
Pleistocene, 149, 157
Pliocene
  conditions during, 149
  oil in, 155
  see also Tertiary
Plugs, igneous, 368
Plunging anticlines, 281, 282
Poland or Galicia, 4
  age of oil, 147, 155, 156
  character of oil, 21, 27
  ozokerite, 42, 85
Pollens, 51, 67, 68, 71
Polymerization, 84
Pool, defined, 9
Pore space in rocks, causes of, 159
  assortment and arrangement of particles, 162
  cementing, 163
  crustal movements, 166
  recrystallization, 165
  shape of particles, 162
  solution openings, 164
  weathering, 167
Porosity, 159
  clays and shales, 175
  conglomerates, 173
  determination of, 168
  effect upon rate of flow of oil, 178
  hybrid rocks, 176
  igneous rocks, 177
  limestones, 173
  metamorphic rocks, 177
  minor sedimentary rocks, 176
  sandstones, 170
Porosity variations
  accumulations due to, 339
  causes of, 339
Pour points, 22
Powder River anticline, 213, 501
Powder River Basin, 289
Powell, 11, 313, 315
Pre-Cambrian time and rocks, 115
Pre-Chattanooga rocks in Oklahoma, 125, 126
Pressure in oil and gas horizons, 202, 207
  capillarity and friction, effect on, 204, 206
  hydrostatic, 202, 207
  initial gas, 203
  origin of, 202
  retention of, 205
Proterozoic age, 115, 116
Province, defined, 13
Puente Hills, 324
Pyrobitumens, 2
  characteristics, 37, 43
  origin, 86
  use in exploration, 484

Q

Quaquaversal anticlines, 269
Quaternary Period, 150
  conditions during, 157
  oil in, 158

R

Radio waves, use in exploration, 493
Ranger district, 33, 104, 217, 346, 414
Rattlesnake pool, New Mexico, 19
Rattlesnake pool, Pennsylvania, 354
Ravenna pool, 322
Reagan County, Texas, 436
Recent time, 149
Recrystallization, effect on porosity, 165
Recrystallization, zone of, 237
Recumbent folds, 252
Red beds, 95
Regional structure in exploration, 487
Regional synclines, oil from, 300
Regional uplifts, 244, 290
Reservoir rocks, 159
Retainer rocks, 159
Reverse faulting, 249
Revived structure, 412
Richland pool, 315
Ring chain compounds, 25, 30
Rising synclines, 302
River deposits
  as containers of oil, 358
  as source beds, 98, 99
Robberson pool, 442
Rocks, nature of oilfield, 168
  as containers or retainers, 178
  classification of, 218
  competency of, 240
Rock pyrobitumens, 37
Rock Springs uplift, 269, 270
Rocky Mountain Province, 12
  age of oil, 135, 137, 139, 141, 148, 154, 155
  general structure, 213, 242, 243, 269
  geologic sections, 140, 268, 278, 289
  producing areas, 266, 269, 274, 276, 287, 420, 428, 434
Rosenberry pool, 354
Rough Creek fault, 320
Roumania, 4
  age of oil, 155, 156
  general structure, 381
  pools and salt structures, 382, 383
Roumanian salt domes and folds, 376
  breccia in, 382
  location and structure, 380
  mechanics of uplift, 395, 400
  oil in, 383
  origin and age of salt, 392
Russia, 4, 7, 170, 172
  age of oil, 155, 156
  bitumens, 43
  character of oils, 17, 18, 23, 29
  geologic section, 156
  producing areas, 357, 423

S

Sabine uplift, 244, 281, 290, 389
Saddles, 293
Sakhalin, 4
Sallyards-Madison shoe string, 362, 365
Salt anticlines, 377
Salt beds, 377
  in relation to occurrence of oil, 94
Salt core structures, 234, 376
  crystal growth theory, 397
  distribution and characteristics, 377, 380, 383, 384, 386
  igneous intrusion theory, 396
  mechanics of uplift, 395
  nature and origin of cap rocks, 402
  oil from, 383, 385, 389
  origin of 392
  plastic flow theory, 399
Salt Creek pool and structure, 170, 184, 290, 293, 366, 428
Salt deposits, indications from 94
Salt Dome field, see Gulf Coast Salt Dome field
Salt domes, 378
Salt stocks, 377
Salzsättel, 377
Salzstöcke, 377
Salztafeln, 377
San Cayetano fault, 331
Sand maps, use of 228
''Sands'' or sand bodies
  channel types, 358
  extent, 340
  large elongated types, 362
  lensing types, 341
  of varying porosity, 345
  ''shoe string,'' 359

Sandstones (including sands)
  as containers, 170
  as retainers, 172
  as source beds, 103, 104
  competency of, 240
  porosity of, 170, 179
San Felipe shales, 104, 141, 175, 366, 475
San Joaquin Valley, 2, 11, 65, 66, 85
  general structure, 241, 244
  geologic section, 301
  producing areas, 264, 301, 302, 305, 306, 335, 355
  waters of, 186
San Juan Basin, 16, 19, 148, 274
Santa Clara fault, 329
Santa Rosa fault, 331
Santa Susana fault, 331
Sante Fe Springs, 253, 254
Sapropel and sapropelic clay, 72, 107
Saratoga pool, 387, 389, 390, 391
Sarawak, 4
Saturated compounds, 25
Saucy Creek anticline, 298
Scotland, 45, 48, 51
Scott-Teeter-Pixlee area, 365
Seal Beach pool, 411
Searight pool, 11, 463
Seaweed as a source of oil, 65
Sedimentary rocks
  as oil containers, 91, 159
  as indicators of oil, 91
  as source beds of petroleum, 91
Sedimentation during folding, 408
Seepages, 7, 84
  asphalt, 40, 484
  gas, 481
  nature and use in exploration, 479
  oil, 480
  relation to regional structure, 487
Seismic methods of exploration, 493, 494
Seismograph, 494
Seminole City pool, 11, 463
Seminole district, 11, 462, 464
Serpentine, oil in, 58, 177, 370
Sewickley quadrangle, Pennsylvania, 193, 194
Shales
  as containers, 175
  as retainers, 175
  as source beds, 103
  burnt, 479
  carbonaceous, 75
  competency, 240
  fissured, 175, 365
  porosity, 175
  production from, 365
  see also Kerogen shale
Shamrock dome, 459
Shamrock saddle, 459
Shannon pool, 428
Shape of particles, effect on porosity, 162
Shear, zone of, 237, 238, 239, 246
Shiell's Canyon, 331, 333
Shirvanskaya area, 357
"Shoe string sands," 359
  Eastern Kansas, 359
  Greenwood Co., Kansas, 362
  Washington Co., Oklahoma, 362
Sicily, 44
Silurian Period
  conditions during, 119
  oil in, 120
  producing areas, 320, 342
Similar folds, 252
Simple symmetrical folds, 252, 253
Smithwick shales, 104, 133, 414
Solidification of oils, 21
Solution openings, effect on porosity, 164
Source materials of oil, 64
Sourlake, 389, 391
South Liberty, 391
South Mountain pool, 331, 333
Specific gravity, 18
Spellacy-Midway anticline, 301, 302
Spindletop, 9, 389, 391, 392
Spore remains, 51, 67, 68, 71, 73
Squeezed folds, 253
Static pressure
  alteration of oil by, 79
  generation of oil by, 74
Station Camp pool, 322
Stereograms, use of, 228, 229, 231

Stillwater pool, 322
Strand line deposits, 101
Stratum field, 13
  see Texas, East-Central and Southwest, and Louisiana, North
Strays, 341
Strike and dip symbol maps, use of, 208, 211, 231
Structures and structural conditions
  burial of, 411
  complex, 408
  "covered," 411
  deep seated, 410
  due to porosity variations, 339
  faulted, 309
  folded, 251
  folded and faulted, 235
  igneous, 368
  local in exploration, 489
  nature in oil fields, 232
  non-producing, 500
  regional in exploration, 487
  representation of, 208
  revived, 412
  salt core, 376
Sub-capillary openings, 160
Sub-Carpathian salt domes, 380
Subsurface exploration, 497
Subsurface maps, use of, 225, 226, 231
Sulphates, see sulphur
Sulphur and sulphur compounds, 2, 15, 30, 39, 40, 41, 82, 85, 182, 183, 184, 185, 186, 304
Sumatra, 102, 155
Sunburst district, 141, 420
Sunset area, 305
Sunset Extension, 355
Sunset-Midway district, 31, 172, 301
Surface geology maps, use of, 208, 209, 210, 211, 231
Surface indications of oil, use in exploration, 90, 479
Surface tension, 22, 23
Swamp deposits, 99, 100
Sweetgrass uplift, 11, 244, 422
Switzerland, 44
Symmetrical folds, 252
Synclines
  regional, 300
  rising, 302
  production from, 297, 301, 306

T

Tamasopo limestone, 141, 174, 366, 475
Tamasopo Ridge, 366, 475
Tampico-Tuxpam embayment, 368, 369, 476
Tar sands, 2, 44, 85, 305, 484
Teapot dome, 293, 428, 432
Tehuacama fault, 312
Tehuantepec, Isthmus of, 155, 383
Tejon shales, 66
Temperature
  in alteration of oil, 78
  in generation of oil, 72
  in migration and accumulation of oil, 200
Tennessee, 6, 126
Tensional faults, 248
Tepetate-Alamo fault line, 312
Terminology, oilfield, 8
Terraces, 281, 306
Tertiary Period, 3, 5, 42, 149
  conditions during, 150
  oil in, 154, 155, 156, 158
  producing areas, 254, 257, 263, 264, 302, 305, 306, 326, 329, 334, 335, 355, 357, 374, 382, 383, 389, 423, 451
Texas, 1, 6, 9, 11
  bitumens in, 44
  characteristics of gas, 39, 40, 60, 203
  characteristics of oils, 18, 19, 33, 34
Texas, East Central and Southwest (Stratum Belt)
  age of oil, 141, 148, 154
  general structure, 310
  geologic sections, 144–145
  producing areas, 9, 312, 317, 370
  salt domes, 384
Texas, North and North Central
  age of oil, 133, 271
  general structure, 245
  geologic sections, 134, 217
  producing areas, 271, 414

Texas, Southern
  age of oil, 155, 156
  geologic sections, 144, 145
  producing pools, 389, 391
  salt domes, 386
Texas, West and Northwest
  age of oil, 97, 135
  geologic sections, 95, 437
  producing areas in, 436, 444
Thomas pool, 471
Thornton, 315
Thrall, 58, 370
Tidal channel deposits, 358
Time, function in oil alteration, 78
Tonkawa, 465
Tools, subsurface, 497
Torbanite, 37, 45, 51, 66
Torchlight anticline, 294, 295
Torrey Canyon pool, 331, 333
Torsion balance, 495
Transylvania, 380, 383
"Trend," 7
Trenton limestone, 119, 174
Triassic Period
  conditions during, 137
  oil in, 137
Trinidad, 4, 172
  age of oil, 147, 155, 156
  bitumens, 40, 41, 484
  character of oil, 17, 18, 20, 22, 31, 34
Trinidad asphalt lake, 40, 484
Trinity sand, 141, 317, 320
Triolefine series, 1, 26
Tuffs, volcanic, 374
Tuxpam district, 18, 475
Tuxpam-Tampico embayment, 141, 368, 476

U

Uintaite, 37, 42
Ulmo-humic matter, 71
Unconformities or unconformable contacts, accumulations at, 355, 413
United-Honolulu anticline, 301, 302
United States, 1, 2, 3, 4, 6, 7
  paleogeographical maps of, 115, 136
  oil provinces of, 12
  see also individual states and areas
Unsaturated compounds, 1, 25, 26
Uplifts, direct, 244
Upper Cretaceous Period
  conditions during, 141
  oil horizons of, 147
  producing areas, 266, 274, 276, 279, 287, 291, 295, 312, 367, 369, 370, 428, 449, 475
Upright asymmetrical anticlines, 257
Upright folds, 252
Upton-Thornton pool, 290
Utah
  age of oil, 135, 148
  bituminous substances, 42, 44, 45, 46, 48, 51
  helium in gas, 40
  salt structures, 376

V

Vacherie salt dome, 385
Valley field of California, 2, 11, 65, 66, 85
  general structure, 241, 244
  geologic section, 301
  producing areas, 264, 301, 302, 305, 306, 335, 355
  waters in, 186
Vanadium in oil, 16, 32, 60
Vander pool, 364
Vegetable origin, theories of, 66
Vein asphalts, 37, 42
Vein pyrobitumens, 37
Venezuela, 4, 11, 172
  age of oil, 147, 156
  bituminous substances, 40
  character of oil, 16, 17, 18, 20, 31, 33, 34
  geologic section, 153–154
Ventura County, California, 332, 334
Victoria-El Abra fault, 311
Vinton, 391
Viscosity, 19
Volatility, 21
Volcanoes, mud, 483

W

Warfield fault and fold, 320
Washington Co., Oklahoma, 362, 363

Water
  in accumulation and preservation of petroleum source materials, 69
  in alteration of oils, 83
  in concentration of oil and gas, 181
  in generation and expulsion of petroleum, 74
  in origin of salt domes, 397
  surface tension of, 24
Waters of cut off basins, 96, 97
Waters, oilfield, 2, 58
  absence in some horizons, 187
  compared with ocean and artesian, 182
  composition, 83, 182, 184, 186
  origin of, 181
Waxes, natural, 37, 42, 85, 484
Wax in oil, 19
Wax, well, 43, 85
Webb-Zapata County fault, 312
Well logs, use of, 218
  accuracy of, 220, 221, 223
  graphic, 219
Well wax, 43, 85
West Columbia, 34, 391
Western Hemisphere, oils of, 34
West Texas, see Texas, West
West Virginia, 6
  age of oil, 122, 124, 126, 127
  bitumens, 485
  character of oil, 19, 22, 33, 34
  geologic sections, 122, 124
  natural gas, 39
Wheeler Ridge, 264
Wheeler Saddle, 459
Wheeler Terrace, 459
Whittier fault, 254, 324, 330, 336, 411
Whittier pool, 324, 326, 329, 330
Wilcox sand, 348, 426, 462, 466, 471
Wiley Canyon pool, 331, 334
Woodbine formation, 315, 317, 320
Woodsfield pool, 203, 285, 286
Wooster pool, 342, 345
World, production, 4
Wortham, 11, 315
Wurtzilite, 37, 43, 86
Wyoming, 6, 11
  age of oil, 135, 137, 139, 141, 148, 154, 155
  bituminous substances, 45, 46
  character of oils, 19, 20, 31
  general structure, 213, 243, 269
  geologic sections, 268, 278, 289
  producing areas, 266, 276, 287, 295, 428

Y

Yenangyat-Singu anticline, 263

LITERATURE OF THE CHEMICAL INDUSTRIES

On our shelves is the most complete stock of technical, industrial, engineering and scientific books in the United States. The technical literature of every trade is well represented, as is also the literature relating to the various sciences, including books useful for reference as well as those fitted for students' use as textbooks.

A large number of these we publish and for an ever increasing number we are the sole agents.

ALL INQUIRIES MADE OF US ARE CHEERFULLY AND CAREFULLY ANSWERED AND COMPLETE CATALOGS AS WELL AS SPECIAL LISTS SENT FREE ON REQUEST

D. VAN NOSTRAND COMPANY, Inc.
Publishers and Booksellers
8 WARREN STREET NEW YORK

553.28 L72

a39001 007055562b

7 2-1